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NO. 13046

POWDER METALLURGY FORGED GEAR DEVELOPMENT

CONTRACT NUMBER DAAE07-80-C-9115

by
D.H. Ro, B.L. Ferguson and S. Pillay
TRW Inc.
Cleveland, Ohio 44117

and

Donald T. Ostberg
US Army Tank-Automotive Command
ATTN: AMSTA-RCKM
Warren, Michigan 48090

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AD 467 80

U.S. ARMY TANK-AUTOMOTIVE COMMAND
RESEARCH AND DEVELOPMENT CENTER
Warren, Michigan 48090

20020814251

[redacted]

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION 13046	**1b. RESTRICTIVE MARKINGS** None
2a. SECURITY CLASSIFICATION AUTHORITY	**3. DISTRIBUTION / AVAILABILITY OF REPORT** Distribution Unlimited, Approved for Public Release
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) 13046	**5. MONITORING ORGANIZATION REPORT NUMBER(S)** MMT Project 4795083
6a. NAME OF PERFORMING ORGANIZATION TRW Inc. / **6b. OFFICE SYMBOL** *(If applicable)*	**7a. NAME OF MONITORING ORGANIZATION** TACOM
6c. ADDRESS *(City, State, and ZIP Code)* Materials and Manufacturing Technology Center Cleveland, Ohio 44117	**7b. ADDRESS** *(City, State, and ZIP Code)* AMSTA-RCKM Warren, MI 48090
8a. NAME OF FUNDING / SPONSORING ORGANIZATION / **8b. OFFICE SYMBOL** *(If applicable)*	**9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER** Contract DAAE07-80-C-9115
8c. ADDRESS *(City, State, and ZIP Code)*	**10. SOURCE OF FUNDING NUMBERS**

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
-	4795083		

11. TITLE *(Include Security Classification)*

Powder Metallurgy Forged Gear Development (Unclassified)

12. PERSONAL AUTHOR(S)

D. H. Ro, B. L. Ferguson, S. Pillay, D. T. Ostberg

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Year, Month, Day)*	15. PAGE COUNT
Unclassified	FROM SEP 80 TO JUL 84	85 March	122

16. SUPPLEMENTARY NOTATION

121

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*

Powder Metallurgy, Forging, Cold Isostatic Pressing, Die Design, Computer Aided Design, 4600 Steel

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

The purpose of this project was to investigate and develop powder forging methods for producing high-performance gears from sintered preforms.

Three gears have been forged from grade 4600 steel powder to which sufficient graphite was added to achieve the desired final carbon level. The first gear, referred to as the NASA test gear because it was designed specifically for gear testing at NASA Lewis Research Center, was forged from 4620 and 4640 steel powder preforms. This gear was a straight spur gear with 28 involute teeth, a 0.25 inche-(6.35 mm) thick web, and a top and bottom hub. Both net teeth and oversize teeth (0.004 inches grinding stock per side) were forged, with these gears being carburized after forging. Gears were then tested in a four square gear testing rig at NASA under the guidance of Dennis Townsend. Using a maximum Hertzian stress of 248,000 psi at pitch line and a gear rotational speed of 10,000 rpm, gear lives were obtained for these gears.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	**21. ABSTRACT SECURITY CLASSIFICATION**

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE *(Include Area Code)*	22c. OFFICE SYMBOL
DONALD T. OSTBERG	(313) 574-5814	AMSTA-RCKM

DD FORM 1473, 84 MAR

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Unclassified

A Weibull plot of gear test data shows that the life of the carburized P/M 4620 gears far exceeded that of through-hardened 4340 steel gears which were machined from bar stock. As-forged teeth produced more scatter in data than forged and ground teeth, with the B-10 life improving from 5 million for net forged teeth to 13 million cycles for ground teeth, where 0.008 inch (0.2 mm) of stock was removed per tooth face. For comparison, aircraft quality 9310 gears have a B-10 life of 18 million cycles. There is a difference in case hardness, between the conventional and P/M gears (Rc 58 for the powder forgings vs. Rc 60-62 for the 9310 carburized gears). From these results, it is clear that powder forgings can perform under conditions of high cyclic loading. For aerospace applications, tooth grinding should be incorporated as a process step.

The second gear that was forged from sintered powder preforms was the No. 6 gear in the AGT-1500 turbine engine accessory gear box. This straight spur gear represented an added level of difficulty because of the 61 teeth of high length, the thickness ratio, and the thickness of the gear. Gears were forged from 4640 and 4660 steel powder preforms over a range of forging conditions to examine the effect of forging temperature on surface finish and dimensional control. In addition, the critical areas of decarburization during processing and response to heat treatment were examined. A set of gears with forged plus ground teeth was prepared for engine testing and delivered to TACOM.

The third spur gear forged from a sintered preform was a power take-off gear for the M2 Infantry Fighting Vehicle. This gear was a ring gear with a high tooth length, thickness ratio, and a thin ring wall. Because of this geometry, die chill and cracking during forging represented major problems. Proper preform design and process control were of prime importance in overcoming these problems. Gears were forged from 4640 and 4660 steel powder preforms over a range of forging temperatures to examine workability and die chill problems. For these ring gears, a preheat temperature of 2200°F (1204°C) was found to be needed to avoid cracking and die fill problems. A set of gears were forged, heat-treated, finish-ground, and delivered to TACOM for subsequent engine testing.

Manufacturing cost analysis showed that P/M forged gears offered cost reduction potential in comparison to the cost of gears manufactured in accordance with current procurement specificaitons.

FOREWORD

This final report covers work performed from September 1980 through July 1984 under Contract DAAE07-80-C-9115. The contract was managed by the US Army Tank-Automotive Command (TACOM), Warren, Michigan, with Mr. D. T. Ostberg serving as Program Monitor.

The program was assigned to the Powder Technology Section of TRW Materials and Manufacturing Technology Center (MMTC) under Mr. J. N. Fleck, Section Manager. Technician responsibilities were carried out by Mr. J. C. Arnold, Mr. D. C. Halliburton, and Mr. J. Schultz. Engineering responsibilities resided with Dr. S. Pillay for Computer Aided Design (CAD), Dr. B. L. Ferguson for Phase I and part of Phase II, and Dr. D. H. Ro for Phase II and III. Mr. F. T. Lally, Consultant, provided support in the area of tool design. Mr. D. Towsend of NASA Lewis Research Center was responsible for rig testing powder/metal forged gears in a cooperative program.

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1.0. INTRODUCTION

The forging of porous performs produced by powder metallurgy (P/M) techniques into structural components having mechanical properties equivalent to wrought properties is a demonstrated technology. The ability to produce net or near-net surfaces with powder forging result in manufacturing cost savings. Previous Army-sponsored programs have shown that powder forging can be used to produce high-performance parts economically for military applications (Reference 1-3). However, the flexibility of the process has been one reason for slow implementation. Many questions regarding effects of manufacturing variables on part quality and performance exist. It is useful to review the findings of previous studies, and organize these results into a handbook-type format so that the results gained in this study can be added to fill in answers to questions remaining about powder forging.

1.1. Background on Previous Army-Sponsored P/M Forging Programs

Three previous programs sponsored by the Army provide relevant background data in this study. These programs are reviewed briefly, with key results presented below.

1.1.1 Machine Gun Accelerators. The purpose of this program was to produce, by powder forging, a high-performance component having a complex shape to demonstrate that parts having properties equivalent to wrought properties could be produced at a cost savings. The part selected to be forged was the accelerator for the M85 0.5 caliber machine gun. The material selected was 4640 water-atomized steel powder. The selection of processing variables was a key facet of the program. Test bar forging and mechanical and metallurgical evaluation provided the basis for process variable selection.

Test bars were compacted at pressures of 30, 40 and 50 tons per square inch (tsi). These test bars were then sintered at 1800°F, 2050°F and 2400°F in dry hydrogen or dissociated ammonia (DA) atomsphere for one hour. Test bars sintered at the two lower temperatures increased in density by 1 to 2 percent of theoretical, while those sintered at 2400°F increased in density by 3 to 4 percent of theoretical. Hydrogen and DA atmospheres had similar effects on microstructure. Based on these results, preforms for forging were sintered at 2050°F for one hour in dry hydrogen after being compacted at 12.5 tons per square inch tons per square inch (tsi), which produced a density of 70 percent of theoretical, or at 30 tons per square inch (tsi), which produced a density of 85 percent of theoretical.

Test bar forging was performed using forging pressures of 20, 30 and 40 tons per square inch (tsi), with preform preheat temperatures of 1600°F, 1800°F, 2000°F and 2200°F, and die preheat temperatures of 300°F to 350°F. A colloidal graphite in water lubricant was applied to the tooling.

Preforms were heated in argon. The preforms in this case fit tightly into the die cavity, with a clearance of 5 percent of die cavity width. Results showed that preform density had no effect on forged density. Preforms temperature and forging pressure had a significant effect on density, however. Presumably because of die chill, the preform required a preheat temperature of at least 2000°F, and a forging pressure of 40 tons per square inch (tsi).

Mechanical property determination showed that property levels were most dependent on final forged density. Yield and ultimate tensile strength equivalent to wrought levels was achieved at forged densities above 98 percent of the theoretical. Ductility and toughness equivalency required densities of at least 99.5 percent of the theoretical. Charpy V-notch values for the P/M forgings include room temperature toughness of ≈ 50 ft. lbs. and -40°F toughness of ≈ 18 ft. lbs. This is similar to the published values for wrought 4640. Rotating beam fatigue testing showed that P/M forged 4640 steel had a fatigue resistance similar to wrought 4340 heat-treated to the same hardness level. Preform density had little effect, except that forgings from preforms of 70 percent initial density had more scatter in properties than forgings from higher density preforms.

Compaction was performed in tooling with a split lower punch so that the proper mass distribution could be achieved in the compact. Because forging of this preform required no lateral flow, the proper mass had to be present in each section of the preform prior to forging. This necessitated using split punches during compaction. Forging was performed with single piece punches. Based on these results, process variables selected to forge the accelerator were a compaction pressure of 30 tons per square inch (tsi), and a sintering temperature of 2050°F for 60 minutes in a hydrogen plus 1 volume percent (v/o) methane atmosphere, preheating the preforms to 2200°F in hydrogen plus 1 volume percent (v/o) methane, followed by forging in trapped dies. The tooling was preheated to 400°F and was lubricated by a graphite in water spray. The forging pressure was 40 tons per square inch (tsi), and as before, a hydraulic press was used for forging.

Mechanical properties of heat-treated test bars sectioned from accelerator forgings showed that tensile and impact properties similar to wrought components were achieved. Most importantly, actual component tests under Army supervision showed that P/M forged accelerators exceeded specifications and had superior wear and fatigue resistance.

1.1.2 Differential Gears. The purpose of this program was to establish manufacturing techniques and cost information for the production of automotive-type gears for ordnance application by powder forging (Reference 2 and 3). Phase I of the program was to define the process parameters for producing high-performance gears. In Phase II, the process was demonstrated by producing 300 gears and performing a cost analysis to examine process economics; gears were then field-tested. The differential gear and mating pinion in the differential of an Army light-duty truck were selected as the demonstration components. The material selected was 4600 water-atomized steel powder.

The process selected for gear forging was cold compaction of a preform of simple shape, sinter, and hot forge. Preforms were compacted at 30 tsi to a density range of 6.4 to 6.6 grams per cubic centimeter; a lower compaction pressure of 20 tsi resulted in preforms that suffered surface cracking during forging. Compacts were sintered at 2200°F for 60 minutes in dry hydrogen plus 1 volume percent methane. Ideally, preforms could be forged directly as they exit from the sintering furnace. For cases where preform preheating from ambient was needed, preforms were heated to 2200°F in hydrogen plus methane in as short a time as possible (approximately 20 minutes). Forging consisted of forward extrusion of bevel gear teeth and back extrusion of the shaft in the case of the differential gears, and forward extrusion alone of the involute teeth for the bevel pinion. The tools were preheated to 400°-600°F and sprayed with graphite in water for lubrication.

Both hydraulic press and crank press forging were evaluated. In this case, there was a decisive advantage to forging on a crank press. In crank press forging, the gear teeth are completely formed at an early stage of the deformation process, with final deformation being back extrusion of the shaft. In hydraulic press forging, the teeth started to form first, but then the shaft was formed before tooth definition was complete. After the shaft was formed, the tooth definition was completed. This sequence of deformation is undesirable since the critical region of the part is the tooth region, and this was the last region to densify and fill.

Field testing of these gears resulted in a satisfactory performance. Metallurgically, the powder forged steel was similar to its bar stock counterpart. Metal flow at the root and along the tooth face during tooth filling benefited the properties.

1.1.3. Computer-Aided Design (CAD) of Preforms. Rock Island Arsenal sponsored a program at the University of Pittsburgh to demonstrate the capability of designing porous preforms for powder forging using a computer (4). Preform design is critical to the success of the powder forging operation because of the inherently poor workability of porous preforms. Prior to this study, preform design involved a combination of experience and guesswork, often resulting in high tooling costs and long development times as compaction die design changes were required. Through computerized preform design techniques, the preform could be designed interactively on the computer, thus eliminating much of the trial and error associated with traditional preform design.

TABLE 1-1. Summary of Process Variables from Previous Army-Funded P/M Forging Programs

MATERIAL: Water-Atomized 4600 + Graphite + Lubricant Addition

- Powder Size Distribution: -100 mesh with -325 mesh fraction being < 30 percent
- Particle Shape: Irregular
- Chemistry of 4600 Powder:

	Ni	Mo	Mn	Si	S	P	Cr	O	Fe
weight	1.65	0.3	0.2	<.05	<.04	<.04	-	0.15	Bal.
percent	2.00	0.5	0.3						

COMPACTION: 30 tsi to achieve at least 80 percent of theoretical density

SINTERING:

- Temperature: at least 2050°F, but 2200°F is preferred
- Time: 60 minutes
- Atmosphere: -hydrogen (-20°F dewpoint) plus 1 to 2 volume percent methane
  -dissociated ammonia is alternate
  -flow rate (not specified)

FORGING:

- Press Type: hydraulic (acceptable) or crank (favored)
- Pressure: dependent on part shape (25 to 40 tsi for hydraulic press)
- Preform Preheat: at least 2000°F
- Die Preheat: at least 300°F (400°F to 600°F favored)
- Die Lubricant: graphite in water applied by spraying

A program was developed that included a geometric description to allow parts to be described in terms of X, Y, and Z coordinates. Furthermore, the part could be sectioned interactively into zones for preform design. Based on a preform shape input by the user, the computer would analyze the preform with regard to the part shape to determine the success or failure in forging that particular preform. By performing trial and error preform design on the computer, much time and cost could be saved.

The CAD concept was demonstrated on a machine gun component. A preform was designed using the interactive program. Tooling for forging was built, and several parts were forged successfully. As a check, another preform shape was also forged. The program predicted failure for the second shape, and indeed, the second preform shape cracked during forging.

1.1.4. Background Summary. The findings of the previous powder forging program are summarized in Table I. Clearly, commercially available water atomized 4600 grade steel powder is capable of being processed into high-performance components. The sintering conditions used in previous studies are more stringent than those employed for conventional press/sinter powder metallurgy parts. Also, the use of a hydraulic press for forging makes the selection of forging process variables different than those selected for commercial powder forging operations using mechanical presses. For example, 2200°F is a higher than normally used preheat temperature and was selected to compensate for the slow ram speed of the hydraulic press. As a consequence, the H-21 steel used for the forging dies deformed under load. In spite of these limitations, the studies showed that dimensional reproducibility could be achieved for critical shapes, and the powder-forged components performed adequately in service for ordnance and automotive applications.

While a computer program of the type discussed was not available for this study, the success of the CAD approach to preform design influenced the preform and die design to be performed. Analysis of a part by sections, where variations in metal flow define sections, proved to be an important aid to preform design.

1.2. Scope of Program

The scope of this program was to build upon past experience to develop manufacturing process data concerning powder forging of high performance gears. Both test gears and actual components would be forged from porous preforms and tested to demonstrate performance capability. Gears were selected as the component for demonstration because of the cost reduction potential of powder forging net or near-net teeth at no sacrifice to the performance.

2.0. PROGRAM OBJECTIVES

The objective of this program was to investigate, characterize, and provide for the evolution of manufacturing process routings applicable to the production of high-performance gears by powder metallurgy techniques. A three-phase program was carried out to achieve this overall goal. Both test gears and real components were forged from sintered steel powder preforms in this effort. These phases are defined in the following sections. An underlying theme throughout the program was cost reduction.

2.1. Phase I. NASA Lewis Research Center Test Gear

A spur gear used in gear rig tests at NASA Lewis Research Center was selected for the first phase of this program. Gears were P/M forged from both 4620 and 4640 steel powder preforms, heat-treated and finished, and then tested in NASA's 4 square gear testing rig. A large data base for aerospace gear materials, including carburized 9310 steel, already existed for this rig test.

Three major goals were to be achieved in this phase. First, through-hardened gears of 4640 composition were compared to case-hardened gears having a nominal composition of 4620 steel powder. Second, net teeth and teeth finished by grinding were tested to determine any differences in performance between these teeth. Third, the concept of using interchangeable die inserts to reduce tooling costs would be demonstrated.

Other goals of this phase were to evaluate the effect of forging temperature on gear characteristics and tooling, and to apply computer-aided perform principles to preform design.

2.2. Phase II. AGT 1500 No. 6 Accessory Gear

The second phase objective was to P/M forge the No. 6 accessory gear for the AGT 1500 turbine engine used in the Abrams tank. CAD techniques were to be used for preform design. These gears were forged using the same die set as in Phase I, with different punches and die inserts being required. This gear represented an increase in complexity of shape over the Phase I gear by virtue of its tooth geometry.

Based on the outcome of Phase II, the next step in this process evolution was penetration into the helicopter gear market. These gears are very expensive due to the precision requirements, and P/M forging offers considerable cost saving potential.

2.3. Phase III. M 2 Gear

Redirection of the original program substituted a power take-off pinion gear for the M113 personnel carrier in place of a helicopter gear. The gear selected, Part No.12298635, was a ring gear for which P/M forging offered significant cost reduction potential. Again, this gear represented an increase in complexity from the previous phase. The thin ring wall and the tooth geometry, while offering cost reduction potential, also posed workability and die chill problems to be overcome.

3.0. CONCLUSIONS

Based on the results of this program, the following conclusions were drawn:

- o Manufacturing cost analysis showed that P/M forged gears offered cost reduction potential compared to the cost of gears manufactured in accordance with current procurement specifications. For an automated P/M forging line, the AGT 1500 No. 6 accessory gear and the M-2/M-3 power take-off gear can be produced at a cost reduction by 75 percent and 50 percent, respectively.

- o P/M forging is definitely a suitable manufacturing process for high-performance military gears. The success in forging three widely different spur gears (i.e., NASA test geat, AGT 1500 No. 6) flexibility of the process and the capability of forging difficult gear shapes from sintered steel powder.

- o The exact form of the P/M forging process and the gears depend upon the nature of the gear. Highly stressed gears of aerospace quality can be powder forged, but finish grinding is necessary to achieve the required surface finish and tolerances of American Gear Manufacturers (AGMA) qualities 10 and higher. As the load level and AGMA quality drop, the as-forged tooth surfaces (i.e., net-size tooth shape) become acceptable as long as the forging process is properly controlled.

- o Proper preform design by computer aided design and control of the forging process resulted in dimensionally accurate gears that were free of forging imperfections. The NASA test gear was successfully forged from sintered preforms of 4620 and 4640 steel powders. Two successful process routes were established.

- o Forged AGT-1500 No. 6 accessary gears were successfully produced from 4600 steel sintered preforms. The importance of preform weight control was demonstrated. The suface finish of the gears forged at 1800°F was superior to that of gears forged at 2200°F.

- o The thin ring wall and the large tooth of the M-2 power take-off gear presented design and workability problems. Die chill in combination with high lateral strains caused a die fill problem for preforms preheated at temperatures below 2200°F. At 2300°F, die fill was improved.

- Ejection is more critical for P/M forgings than for conventional forgings because there are no draft allowances in the former. Special attention should be given to die design in relation to contraction of the workpiece onto the core rod.

4.0. RECOMMENDATIONS

Based on the results of the gear forging phases of this program, the following recommendations are proposed:

- P/M forging of gears should be designated as an acceptable manufacturing method for many military gears. Automotive gears, and many power transmission gears can now be produced from forged P/M steels with no reduction in part performance.

- Further work should be carried out to explore the substitution potential of forged P/M gears for machined "cut" helicopter gears, highly loaded transmission gears, and other precision gears. New alloy steels and new powder types, such as oil-atomized powder with lower oxygen levels and chromium-bearing steel powders, should also be included.

- This program only scratched the surface of implementation of CAD to die and preform design; more emphasis should be put on this area. The production of precision parts requires accurate design models. The use of the computer must expand in these areas for efficient production of precision hardware.

- A program to establish automated manufacturing procedures for forged P/M gears is needed to take advantage of precise control of forging processes. Implementation of computer-controlled forging equipment, robot transfer devices, and tooling produced by CAD/CAM techniques will be needed to allow precision forging processes to penetrate military and commercial markets to a greater degree than they already have.

- It is necessary to establish quality control proedures and acceptance/rejection standards for use by the gear designer to allow incorporation of forged P/M gears into critical applications.

5.0. DISCUSSION

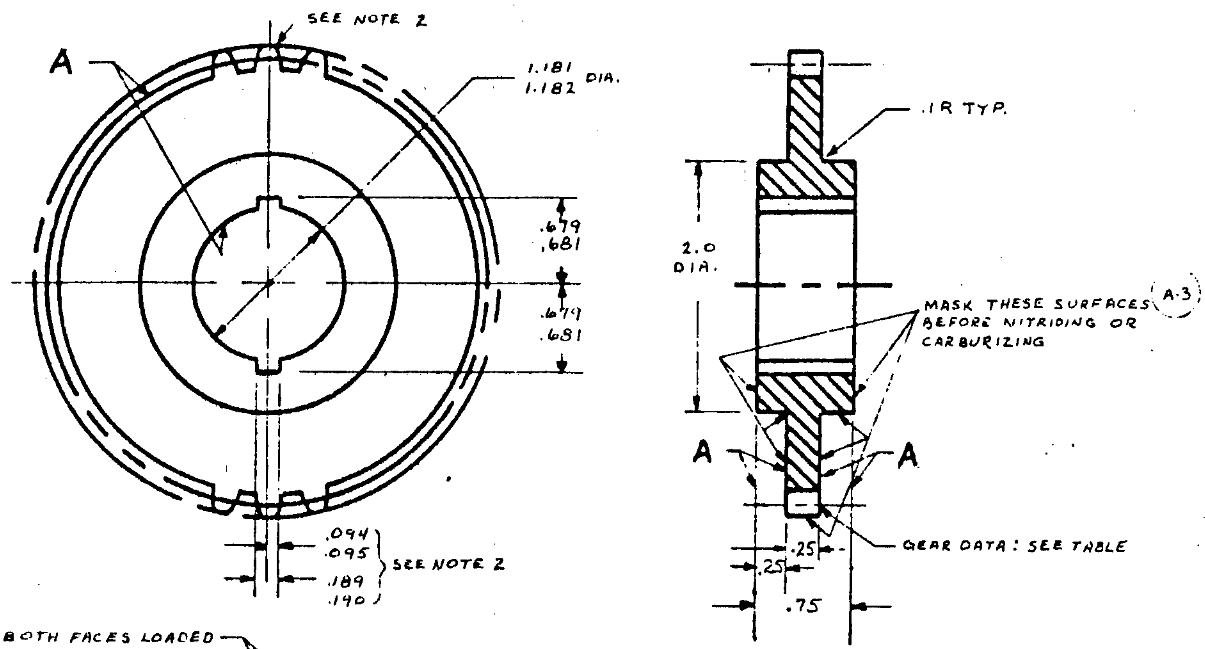
5.1. NASA Test Gear (Phase I)

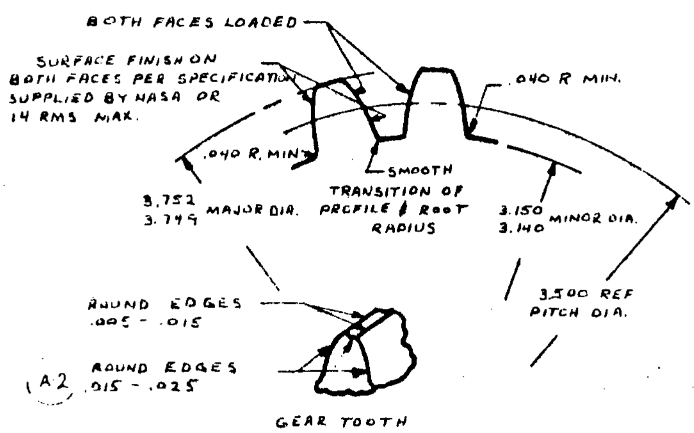
The standard test gear used at the NASA Lewis Research Center for gear development studies is shown in Figure 5-1. This gear is a straight spur gear with 28 involute shaped gear teeth. It also has a top and bottom hub, with a central bore. P/M forging of this gear represented a challenge due to tight dimensional tolerances and the long, thin tooth profile.

5.1.1. Preform Design and Production. Professor Howard A. Kuhn of the University of Pittsburgh was contracted to design the preform for the NASA test gear. The computer program developed previously was not capable of designing gear preforms because axisymmetric shapes had not been included in that development effort. However, as co-developer of that program, Professor Kuhn was able to use the same design approach for this gear preform as was build into the computer program.

In order to implement CAD of preforms for future preform design tasks, the software developed at the University of Pittsburgh (see Ref. 3) was modified to run on TRW's IBM computer system. The graphics portion of the software was modified to accept a geometric description of the spur gears. This enhanced the original software to allow cross sectional area and volume calculations of spur gears. Details on the geometric description and calculations are contained in Appendix A.

5.1.1.1. Workability Characterization. The first step in preform design was to characterize the workability of porous preforms of 4620 and 4640 composition. Water-atomized 4600 V low alloy powder (Hoeganaes Corporation's forging quality powder) was blended with graphite to achieve the desired carbon levels. Right circular cylinders were pressed in a double acting die set to a height of 0.65 inches (0.017 m) and diameter of 1.000 inches (0.025 m). The compacts were sintered at 2200°F (1204°C) in hydrogen plus 1 volume percent methane for one hour at temperature, to an as-sintered density being of 80 percent of theoretical. These samples were then isothermally compressed between flat dies with controlled friction conditions. Room tempreature comparison tests were performed on a Baldwin universal testing machine at a constant ram speed of 0.5 in/s (0.013m/s). The friction conditions examined were: rough dies, smooth dies, smooth dies lubricated with molybdenum disulfide grease, and smooth dies sprayed with Teflon. Elevated temperature tests were performed at 1300°F, (704°C), 1350°F (732°C), 1400°F (760°C), 1450°F (788°C), and 1800°F (982°C) on a specially adapted MTS machine at a constant strain rate of 10 per second. The friction





GEAR DATA

NO. OF TEETH - 28
DIAMETRAL PITCH - 8
CIRCULAR PITCH - .3927
WHOLE DEPTH - .300
ADDENDUM - .125
CHORDAL TOOTH THICKNESS REF - .191
HELIX ANGLE - 0
PRESSURE ANGLE 20°
PITCH DIA. - 3.500
OUTSIDE DIA. - 3.750
ROOT FILLET -
MEASUREMENT OVER PINS - 3.7867 - 3.7815
PIN DIA. .216
BACKLASH REF. - .010

GEAR TOLERANCE PER
AGMA CLASS 1 *
A-1 TIP RELIEF .0005 - .0007

Figure 5-1. NASA Test Gear.

conditions for elevated temperature tests were: dry rough dies, dry smooth dies, smooth dies sprayed with graphite in water, and smooth dies lightly coated with glass frit.

The fracture lines resulting from these compression tests are shown in Figure 5-2 for 4620 preforms and Figure 5-3 for 4640 preforms. Fracture lines were determined from surface strain measurements made at the point of fracture. Although scatter is present, distinct workability trends are clear. The fracture lines lie at a slope of 0.5, which is in agreement with other reported results for porous preforms and conventional material (Reference 5-7). The level of the fracture line, indicated by the plane strain intercept value, increases as the test temperature increases, as expected. Above 1400°F, the workability of these materials is not improved substantially by increasing the temperature. Interestingly, 4640 has marginally better workability than 4620 at all test temperatures. The poor workability of porous preforms is reflected by the low level of these lines. For reference, low alloy steel bar used in cold forging applications has a plane strain intercept value of 0.4 opposed to the P/M values, which are all under 0.15, in Figures 5-2 and 5-3.

5.1.1.2. Preform Design. An engineering drawing of the preform for this gear is shown schematically in Figure 5-4. The preform is smooth on the outside diameter, requiring that gear teeth be formed by lateral flow during the forging operation. A top and bottom hub are present initially so that repressing dominates hub fill and densification. The hub and flange are connected by a tapered section. A major point is that this design is based on the starting preform having a uniform density of 80 percent of theoretical.

In Figure 5-4(b) the position of the preform in the die cavity at the initiation of forging is depicted. Contact is made simultaneously along hub and flange surfaces. As tooth fill and hub densification occur, the radius connecting the hub and flange does not move so that it becomes the same radius on the forged part. No metal flow occurs into the hub from the flange, or vice versa, during the forging operation, provided the initial preform density is uniform. In this manner, metal flow is concentrated in the gear tooth region, where it is most beneficial.

5.1.1.3. Preform Compaction in Hard Tooling. To simulate commercial production of these gears, a subpress was employed for powder consolidation. The subpress simulates double action compaction by floating the die body on pneumatic cylinders. The subpress is shown in Figure 5-5 installed in a 150 ton hydraulic press. Two of the air cylinders which support the die table are visible at the front corners of the subpress. The compaction tooling consists of a top punch, a

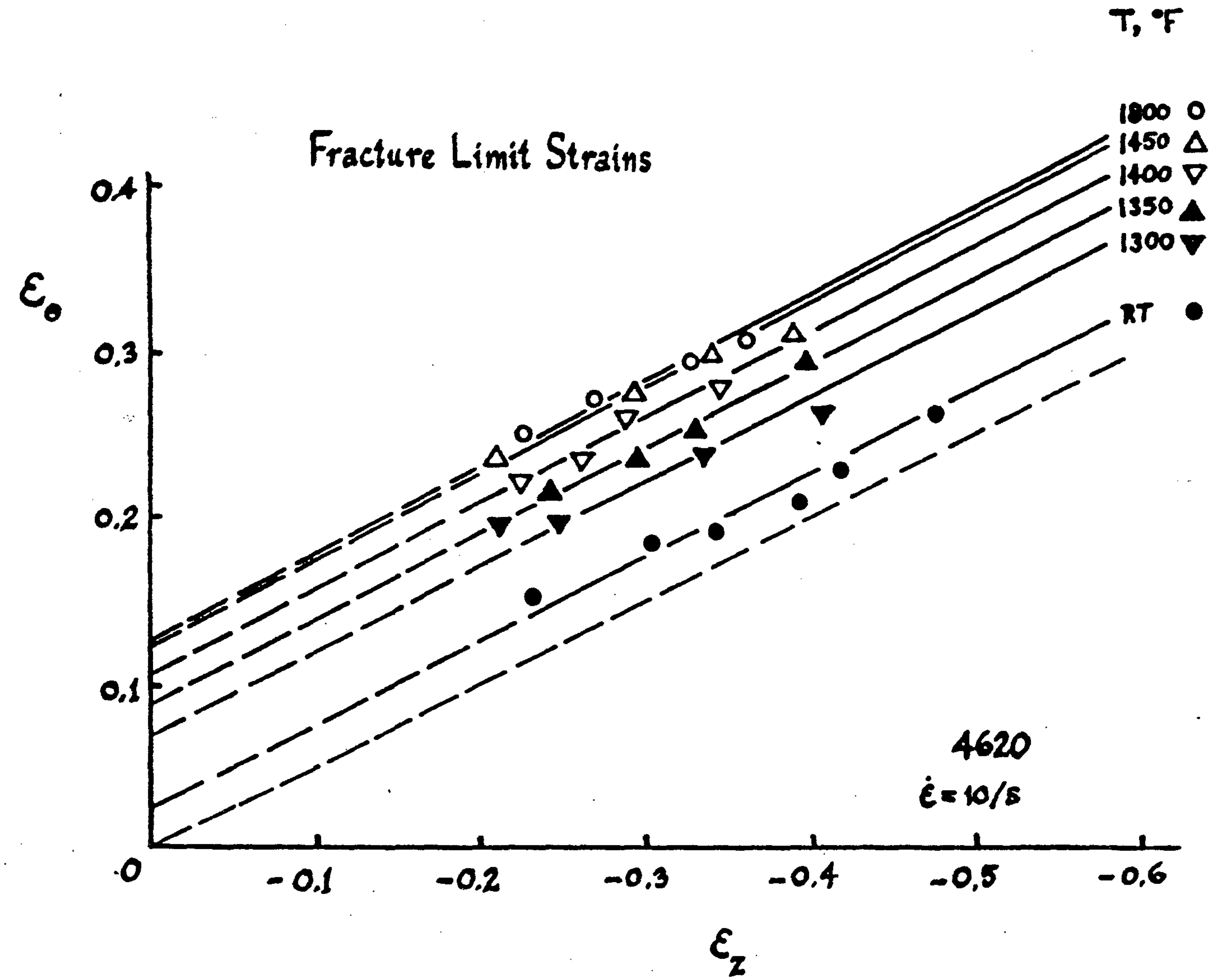


Figure 5-2. Surface Fracture Limit Strains for Upsetting 4620 Steel Powder Preforms with Initial Density of 80% of Theoretical.

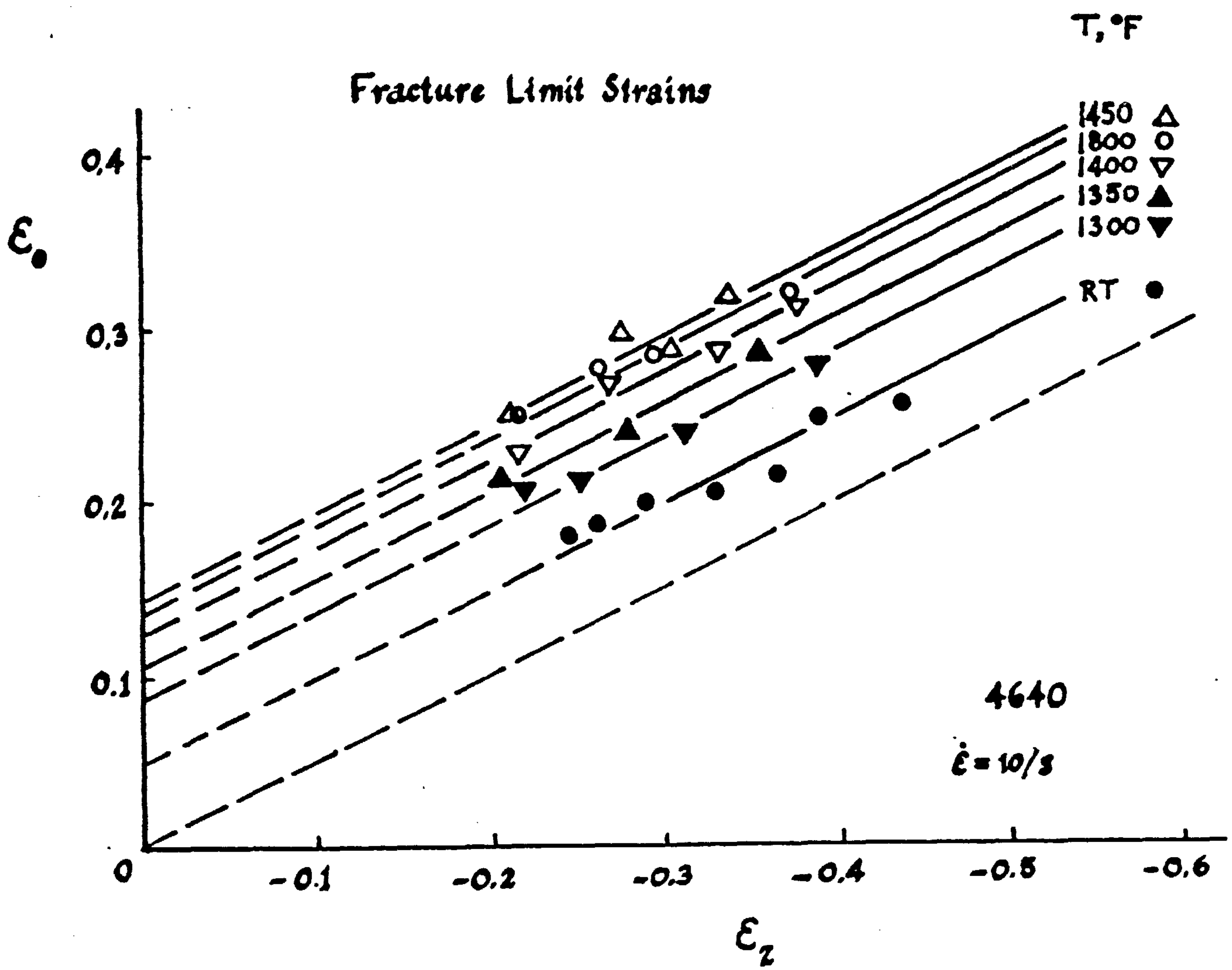
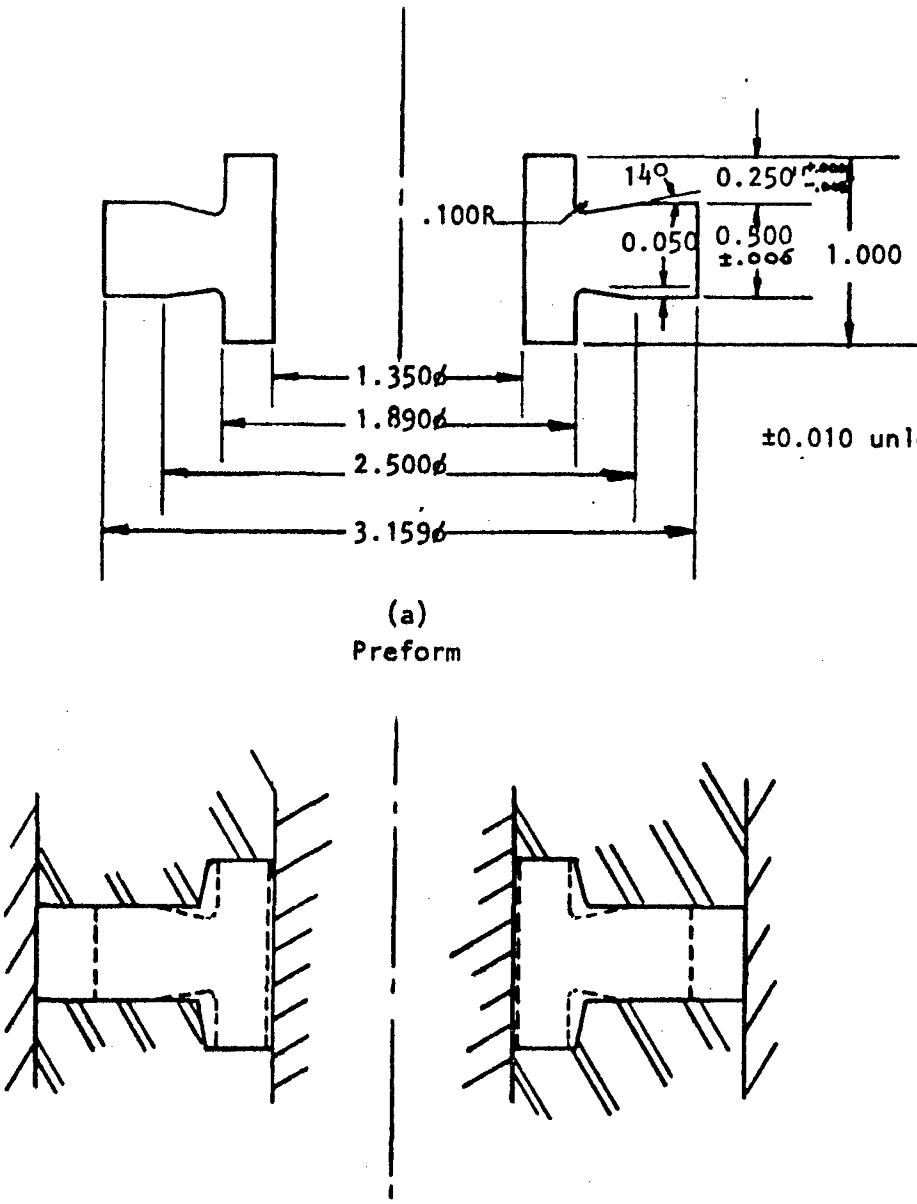


Figure 5-3. Surface Fracture Limit Strains for Upsetting 4640 Steel Powder Preforms with Initial Density of 80% of Theoretical.



(a)
Preform

(b)

Preform in Die Cavity

Figure 5-4. (a). NASA Test Gear Preform.

(b) Position of Preform in Die Cavity.

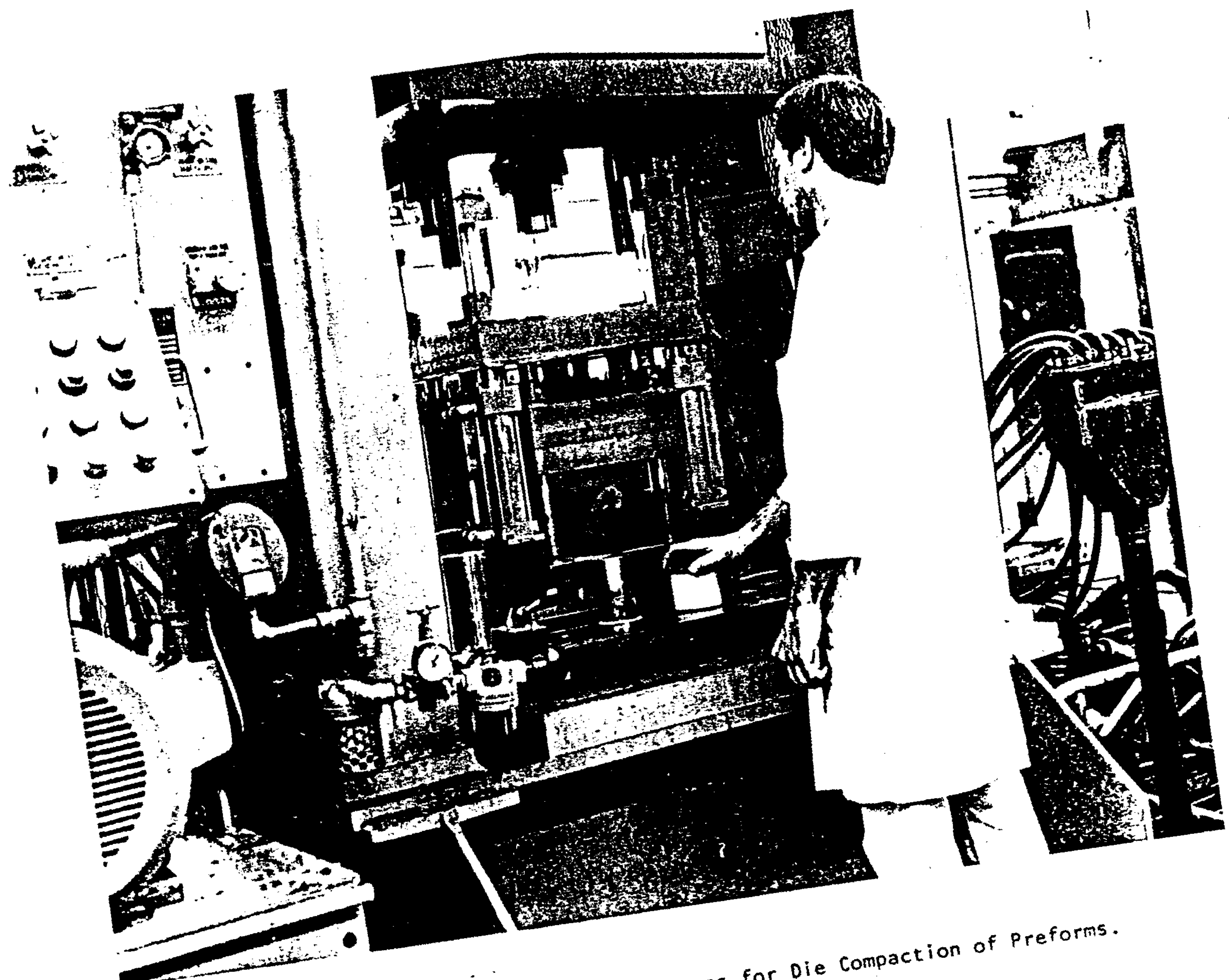


Figure 5-5. Preform Tooling and Subpress for Die Compaction of Preforms.

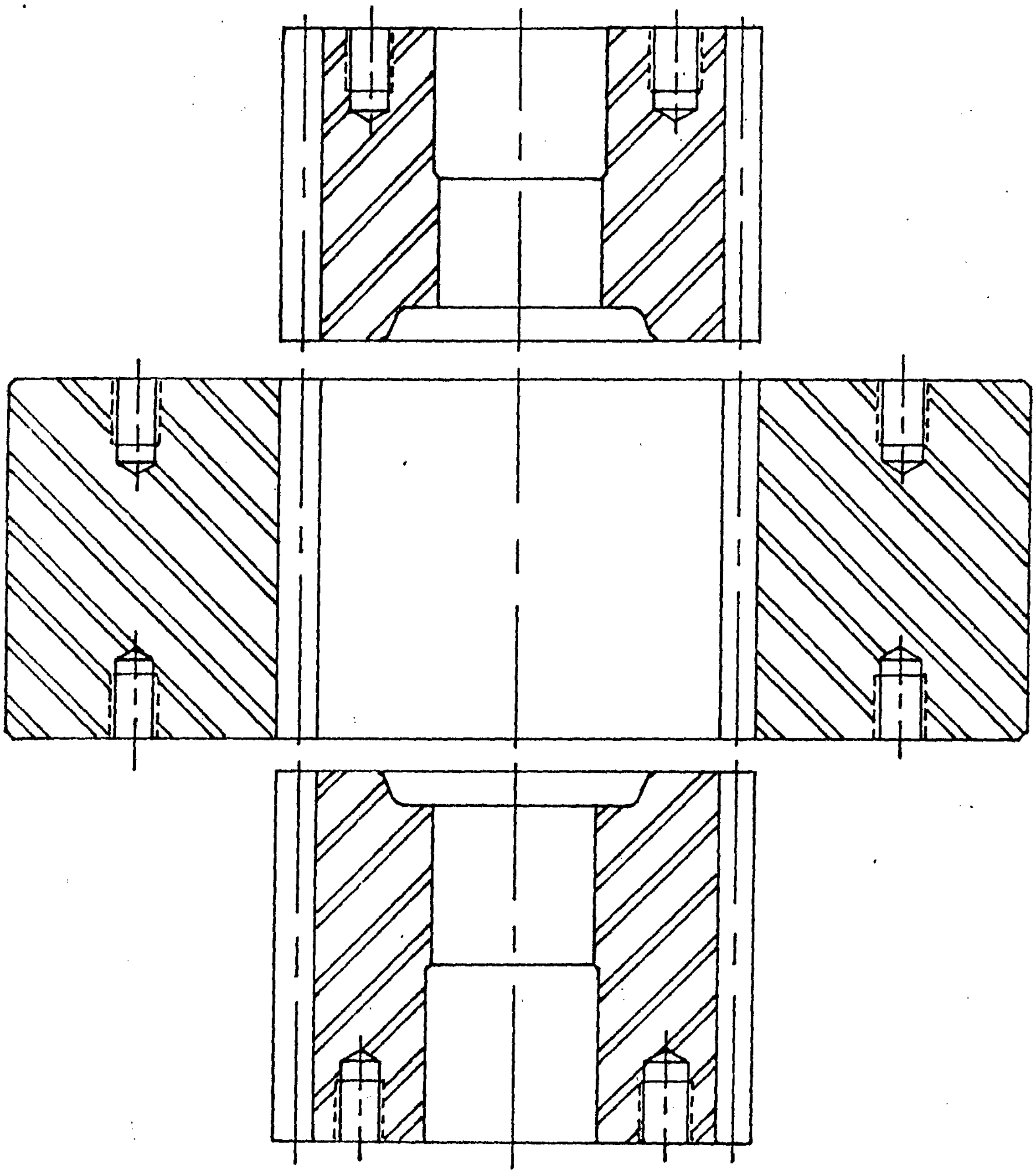


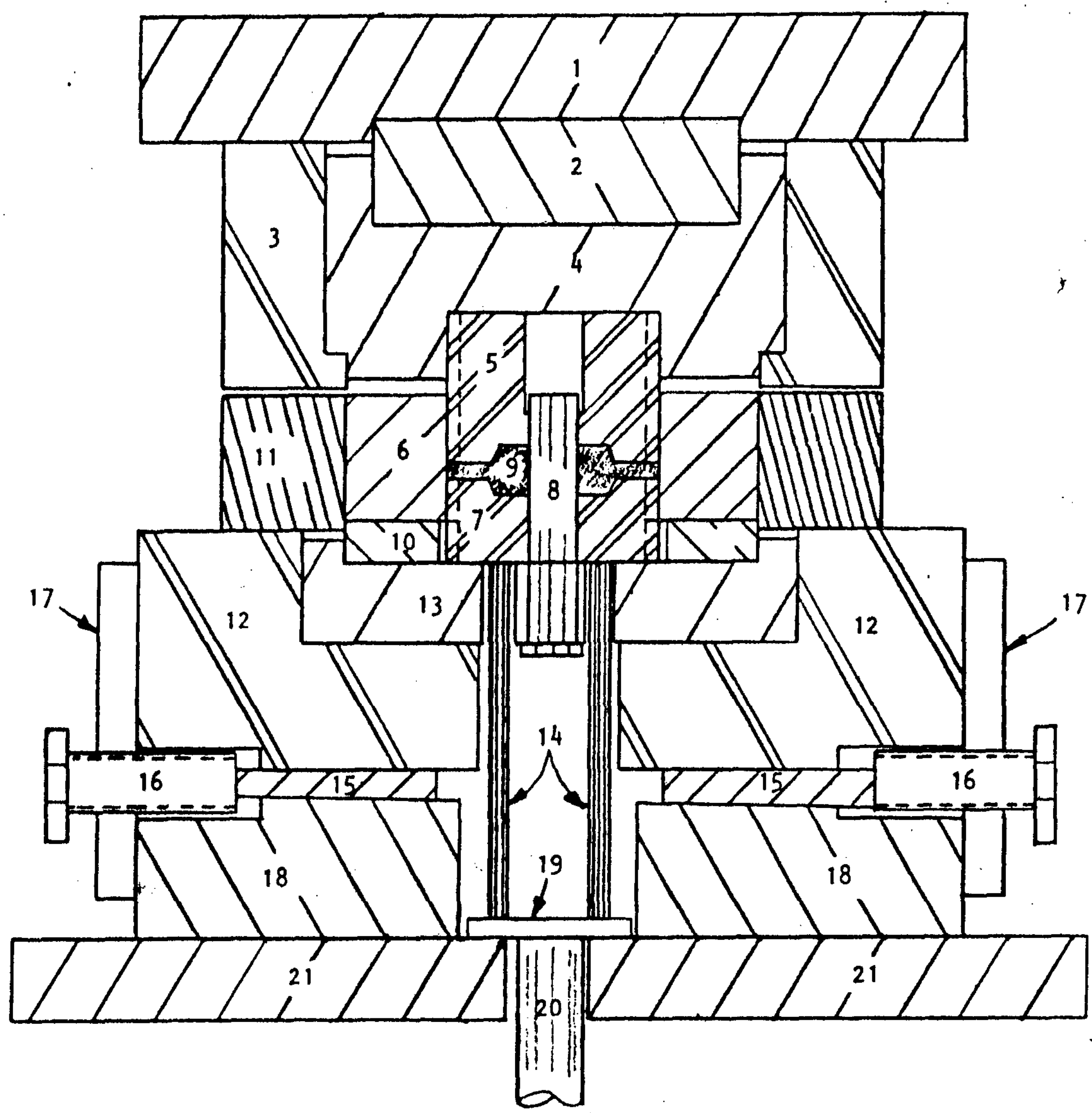
Figure 5-6. Schematic of Compaction Tooling.

ring die, and a botton punch, as shown in Figure 5-6. The ring die forms both the outer diameter of the compact and the gear section by virtue of the integral shelf in the die body. The bottom punch is associated with the hub portion of the preform shape.

The compaction process for this preform includes two stages. In stage I, stop blocks are placed under the die table to restrict motion of the die table. This causes the major load enacted by the advancing top punch to be applied to the gear section of the compact. When the full load of the press has been achieved, the compaction process is interrupted and the stop blocks are removed. Downward motion of the press ram is reinitiated to begin stage II of the compaction process. Now, the die table is free to float, with downward motion occurring as the resistance force of the air cylinders is overcome. Downward motion of the die table causes the hub section of the compact to densify, as the bottom punch remains motionless. The results of this compaction process is that stage I sizes the gear section of the preform and stage II sizes and hub section of the preform. In production on commercial equipment, these stages would occur simultaneously through multiple punch motions, instead of sequentially through the use of an interrupted process.

5.1.2. Design of Forging Tools. The design of forging tooling for this study comprised two major areas. First, a die nest had to be designed that demonstrated the concept of interchangeability of tooling components. Second, the die components for the NASA test gear had to be designed and dimensioned.

5.1.2.1. Die Nest Design. A die nest was designed for P/M forging of parts up to 5 inches in diameter by 2 inches in height. With modifications, other sizes could be accommodated. The die nest consists of a 4 post nest for punch guidance, a top punch assembly, a ring die and ring die support assembly, a bottom punch assembly, and an ejection mechanism. The die nest is shown schematically in Figure 5-7, with the guide posts omitted for clarity. In Figure 5-8, the die nest is shown prior to installation in the 700 ton crank press. The tooling members that comprise the forging or part-shaping members are the ring die, the top punch, the bottom punch and the core rod. Each different part forged in this nest requires a different set of forging members. The concept of this tooling arrangement is that the nest can be used with a wide variety of forging members to minimize tooling costs. At the same time, the design of the die nest should allow fast change-over from one forging shape to another, thus minimizing setup costs.



1 Top Bolster
2 Load Cell
3 Support Ring
4 Backer Block
5 Top Punch
6 Ring Die
7 Bottom Punch
8 Core Rod
9 Forged Gear
10 Die Support Ring
11 Support-Clamp Ring
12 Sub-Backer Block
13 Backer Block
14 Ejector Pins
15 Wedge
16 Wedge Adjuster Screws
17 Alignment Plate
18 Tapered Base Plate
19 Ejector Pin Seat
20 Ejector Rod
21 Bottom Bolster

Figure 5-7. Schematic of Die Set for P/M Forging.

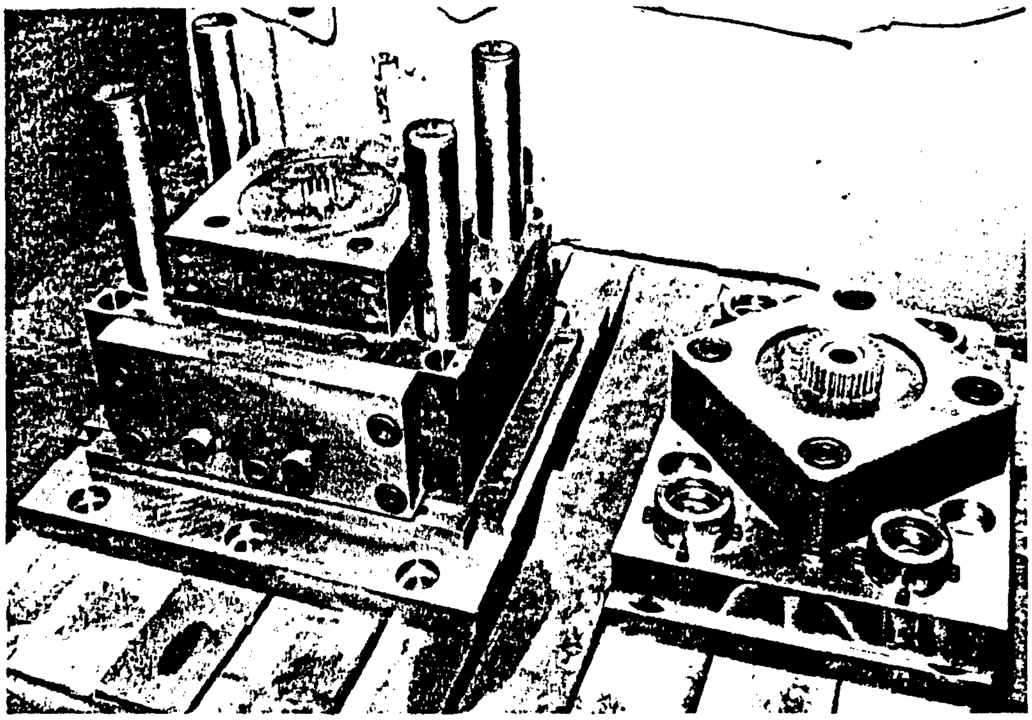


Figure 5-8. NASA Test Gear Forging Die Set.

5.1.2.2. Top Punch Assembly. The top punch assembly was designed to accurately locate the top punch with regard to the ring die. The top punch is bolted to a backer plate which is positioned by a support ring. Notice in Figure 5-7 that provision is made for a load cell to be mounted in line with the top punch for accurate measurement of forging loads. Not indicated by this figure is the fact that both lateral and rotational locations must be established and maintained.

The alignment of the top punch with the ring die is maintained by four guide posts. This arrangement proved to be satisfactory for this study. For more precise alignment, but at a higher tooling cost, guidance by vertical wedges could be used.

5.1.2.3. Ring Die Assembly. The ring die is supported by a split ring clamp which contains two high strength steel bolts that supply clamping pressure. The ring die support contains four horizontally positioned cartridge heaters for control of die temperature. The support ring was designed to provide sufficient support to the ring die for prevention of ring die distortion. In this regard, it is not as efficient as the use of stress rings. For commercial practice, one or two stress rings should be used to provide die support, and the split ring should be used for positioning. Also, the split ring should include either a locking taper or a flange to prevent upward motion of the ring die during ejection of the forging. With repeated forging, some vertical motion of the ring die during ejection was experienced for simple cylindrical clamping with no taper or flanges.

The ring die assembly must mate precisely with the bottom punch assembly for accurate alignment between top punch, ring die and bottom punch.

5.1.2.4. Bottom Punch Assembly. The bottom punch assembly is perhaps the most critical of the die nest components because of the different functions which it must perform. First, this assembly provides support and alignment of the bottom punch. Second, it must provide for vertical positioning of the punch for forging thickness control. (Note: Some presses allow positioning by a ram height location control, which eliminates this function from the bottom punch assembly. Alternatively, hydraulic wedge packages are available for thickness control). Third, ejection capability must be provided.

Support of the bottom punch is provided by a backer block and a sub-backer block. These members are important because the bottom punch is bolted to ejection pins which pass through the backer block and bolt to an ejection plate. A rod connects the ejection plate to the ejection mechanism.

The sub-backer plate rests on a sliding taper plate, which in turn rests on a tapered base plate. Adjustment screws drive the taper plate backwards and forwards for height adjustment of the bottom punch. This arrangement provides fine adjustment of forging thickness.

5.1.2.5. Die Dimensioning. The dimensions of the forged part are determined by preform dimensions and density, the die dimensions, the forging temperature, the die temperature, and the forging cycle time. These variables encompass many other variables and are dependent on many material properties. The achievement of the precise part dimensions on a repeatable basis is dependent on the degree of control of the P/M forging process in terms of temperatures and times, the mechanical and physical properties of the die and workpiece materials, and the repeatability of process times. The interaction of these variables is detailed in Appendix B.

For the NASA test gear, the ring die was dimensioned for forging at a preform preheat temperature of 1800°F (980°C) and a die temperature of 500°F (260°C). The die cavity dimensional data supplied to the toolmaker are given in Table 5-1. The process times were unknown at that point and could not be taken into account for this dimensioning. However, compensation for these unknowns was possible by varying the actual forging variable used. Final forging size was achieved by altering preform and die temperatures. For example, if the forgings are repeatably undersize, increasing the die temperature and/or decreasing the preform preheat temperature will produce larger forgings. Conversely, a decrease in die temperature and/or an increase in preform preheat temperature will produce smaller forgings.

5.1.2.6. Die Manufacture. The forging tool members were manufactured from H-13 die steel. Electrical discharge machining using a traveling wire (wire EDM) was selected as the method for machining the gear shape in the ring die and the punches. Wire EDM is a numerically controlled machining process and is capable of maintaining dimensional accuracy within 0.0002 inches (0.0005 mm). Accuracy of this order is needed in the manufacture of precision forge tools. The wire EDM process guarantees accurate mating of punches and dies. The ring die was machined to the dimensions in Table 5-1. The punches were sized to allow a clearance gap of 0.002/0.004 inches (0.005/0.102 mm) per side.

5.1.3. Forging of NASA Test Gears. Before discussing the actual experimental procedures, the variables present in this powder forging study must be defined. These variables center around equipment, the porous workpiece, and the interaction between equipment and workpiece.

5.1.3.1 Definition of Forging Variables. The significant equipment used for this forging study were the press and furnace. A 700 ton (6.2 MN) crank press with a 10 inch (0.25 m) stroke was selected as the forging press. For preform heating and sintering, a muffle furnace equipped with a dissociated ammonia atmosphere was selected. This equipment is shown in Figure 5-9. The furnace mouth is adjacent to the press to allow rapid transfer of hot preforms to the die cavity.

TABLE 5-1. Dimensions of NASA Test Gear Ring Die Cavity at Room Temperature for Forging of Oversize Gear Teeth.*

Number of Teeth	28
Diametral Pitch	8
Circular Pitch	0.397 in.
Chordal Tooth Thickness (Ref.)	0.223 in.
Pressure Angle	20°
Pitch Diameter	3.534 in.
Major Diameter	3.819 in.
Minor Diameter	3.211 in.
Root Fillet Radius	0.060 in.
Tip Radius	0.010 in.

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* Punches have a 0.002 in. clearance gap per side.

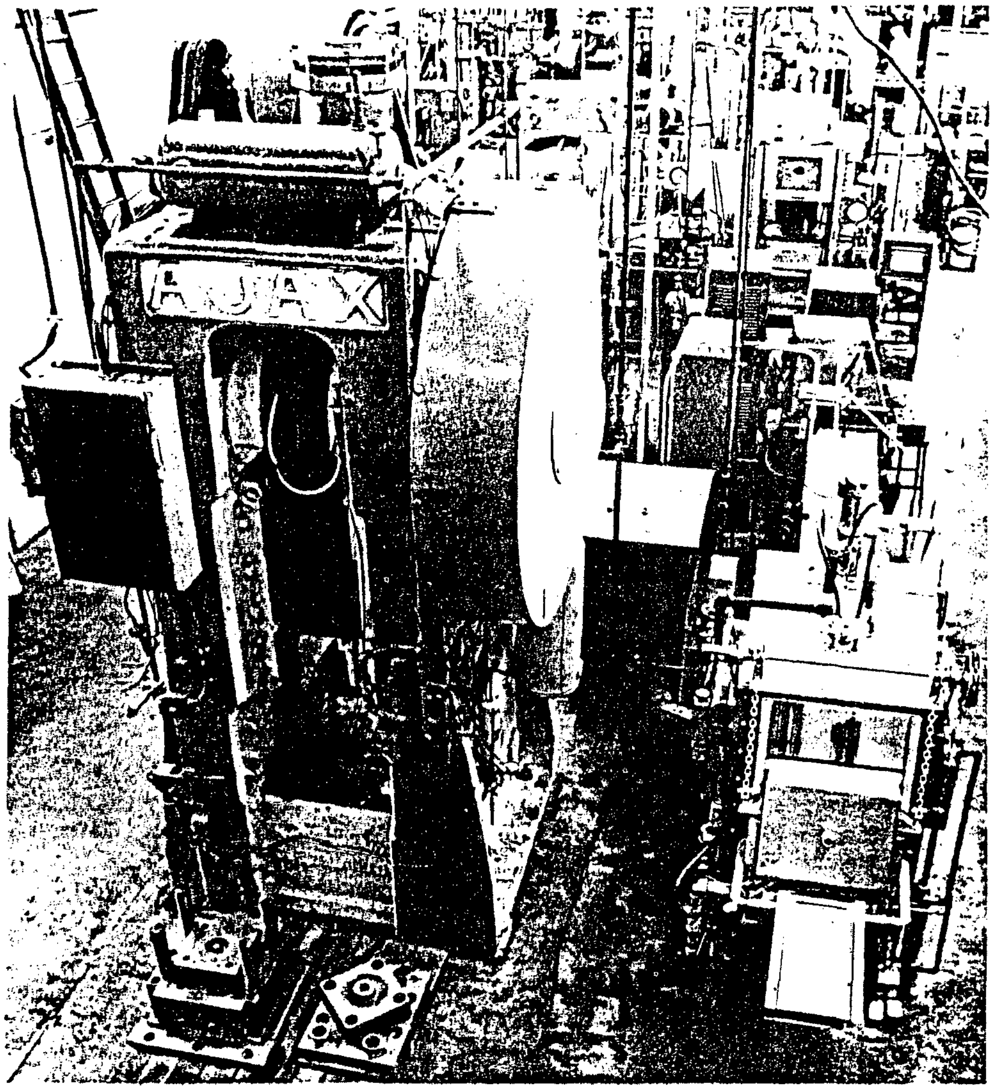


Figure 5-9. Ajax 700 Ton Crank Press and Lindbergh Atmosphere Sintering Furnace Used for P/M Forging.

Because manual transfer of the hot preforms to the die cavity and manual operation of the press were part of the process, the heater and the press operator were other variables to consider.

The process sequence is given in Table 5-2. Variables are indicated for each process step. Several of the variables were assigned predetermined values, as indicated. Reasons for these selections included commercial considerations and prior experience. The variables which had no assigned values were examined in experimental trials.

Preform temperatures over the range 1800° to 2200°F (982° to 1204°C) were examined.

Tool Temperature - Because tool steel dies were used, the preheat temperature was held below 700°F to prevent tempering of the dies. However, cold tools chill the forging and produce surface porosity. Therefore, temperatures between 300° and 600°F (150° to 315°C) were selected for examination.

Forging Pressure - Pressure is a consequence of die fill and flow stress for forging in trapped dies on a mechanical press. For P/M forging, pressures between 30 and 70 tons per square inch (tsi) (414 to 965 MPA) have been reported. For this study, pressure was not a variable. Rather, the press was adjusted to give die fill at a given forging temperature, within the limits of the press. Forging load was measured, however, using strain gages on the press frame.

Time in Tooling - The time that the part is in the tooling should be a minimum for a number of reasons, the two major ones being minimizing heat build-up in the tooling, and minimizing distortion of the part due to nonuniform cooling in the die. Rapid sequencing through the forging cycle minimize this time. For this forging setup, the ejection system was separate from the mechanical advance and retract of the press ram. It is manually operated, using a hydraulic cylinder to raise the bottom punch and push the part from the ring die cavity. Therefore, although the press sequencing was fast, the total time in the die cavity was long compared to that of a production system due to a slow ejection system. For example, for a production setup a total time in the tooling may be on the order of 0.1 second or less. For this setup, the total time in the tooling was at least 2 - 3 seconds.

5.1.3.2. Experimental Procedures. After installing the die set in the press, sintered aluminum preforms 90 percent dense were forged. These were flat doughnut shapes with increasing weight from 95 gm to 127 gm. The doughnuts were heated to 800°F (426°C) and coated with graphite lubricant. The dies were sprayed with graphite lubricant. These trials provided data concerning press characteristics, such as play in the load train. Web thickness of the forged shapes.

TABLE 5-2 Powder Forging Process Variables

Step	Variables Present	Selected Variable Values
Powder Type Selection	-Production Method	Water Atomized
	-Initial Alloy Distribution	Prealloyed
	-Particle Size Distribution	-100 Mesh (Forging Quality)
Compaction	-Lubricant	Zinc Stearate
	-Lubrication Method	Die Wall
	-Compaction Tooling	Tool Steel Dies (Hard Tooling)
	-Compaction Pressure	Sufficient to Densify Powder to 80 percent of Theoretical Density
Sintering	-Atmosphere	Dissociated Ammonia
	-Temperature	2200 °F
	-Time	30 Minutes at Temperature
Forging	-Press Type	Mechanical
	-Preform Temperature	
	-Tooling Temperature	
	-Transfer Time	8 sec.
	-Forging Pressure	Sufficient for Die Fill
	-Time in Tooling	
	-Lubricant	Deltaforge 31 or 33
	-Post-Forging Cooling	Quench in Oil

was measured, and the amount of die fill was examined. Because these were flat shapes initially, the hubs were formed by extrusion and the gear teeth formed by lateral flow. Interestingly, a preform shaped similar to the one in Figure 5-4 (with a weight of 129 gm) gave the best fill and a thinner web than the lighter weight flat preforms. This suggests that preforms which use selective metal flow may achieve die fill at lower press loads. However, it does not offer information concerning the degree of densification.

Eighty percent dense steel powder preforms were next tried. As in the case of the aluminum preforming, the perform weight was initially low and gradually increased for each succeeding trial to avoid die problems. A sintered preform of 364 gm was heated to 1850°F (1010°C) and forged tools to 200°F (93°C). The hub filled completely, but the gear tooth fill was incomplete. Ejection was extremely difficult as the forging contracted around the core rod as it chilled prior to ejection. To circumvent this problem, the core rod was sectioned as shown in Figure 5-10 so that a removable cap was ejected with the forging. The cap could later be removed easily from the forging and reused. After this concept was implemented, several forging lubricants were examined, including Deltaforge 31, Deltaforge 33, Molydag, Fisk 604, Polygraf, and Ceram-guard. Of these, Deltaforge 31 and 33 gave the best overall results from standpoints of lubrication, uniformity of coating, and ease of application. On the basis of these strictly qualitative observations, Deltaforge 31 was chosen as the primary lubricant for the remainder of the project, with Deltaforge 33 being the second choice.

From these trials, satisfactory forgings were produced by preheating the and tools to 550°F (288°C), spraying the green (unsintered, or as-pressed) preforms with Deltaforge 31, sintering (preheating) at 2200 °F (1204 °C) for at least 30 minutes, and Spraying the tools with Deltaforge 31 prior to forging; 30 minutes was required for sintering, as the tooth tips cracked when the preforms were sintered for shorter times.

A point of importance concerning preform design is that forging laps were present on each hub. These laps were caused because the hub and gear tooth sections were not compacted to the same densities. During forging, the gear tooth section reached full consolidation before the hub sections. This resulted in metal flow into the hubs, which moved the corner of the preform onto the hub. Final hub fill axially collapsed this corner to form a lap, as shown in Figure 5-11. Because this lap does not affect the performance of this particular gear, no steps were taken to alter the compaction practice in order to achieve uniform preform density. All NASA test gears contained these laps on the hubs.

5.1.3.3. Forging Trial Results. A series of 4620 and 4640 steel NASA test gears with oversize teeth (0.008 to 0.01 inches grinding stock) were forged using the above conditions.

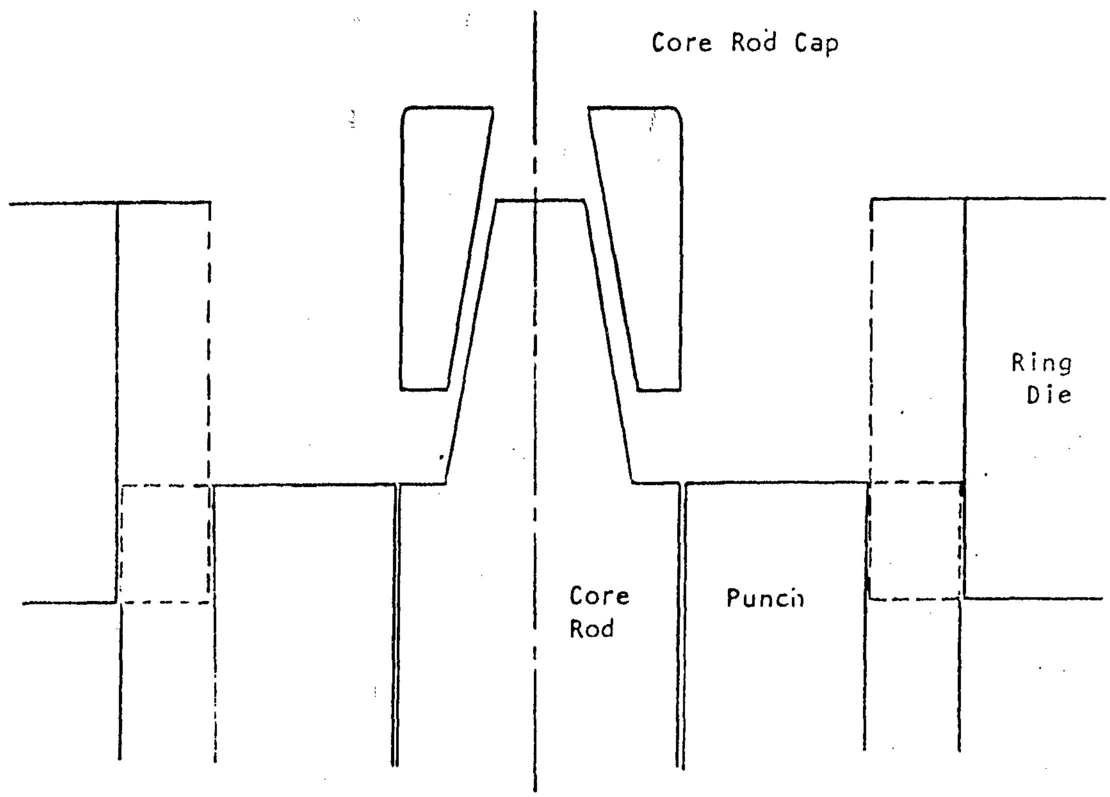


Figure 5-10. Segmented Core Rod Concept for Reduction of Ejection Load.

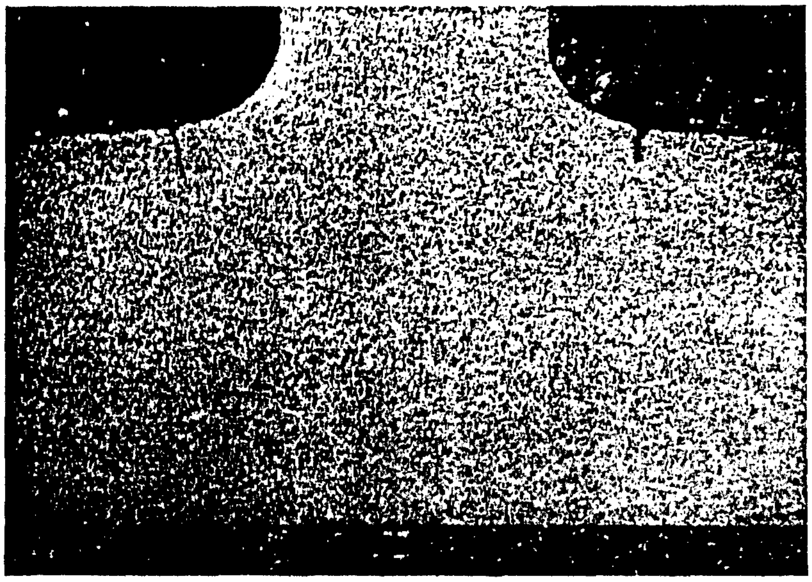


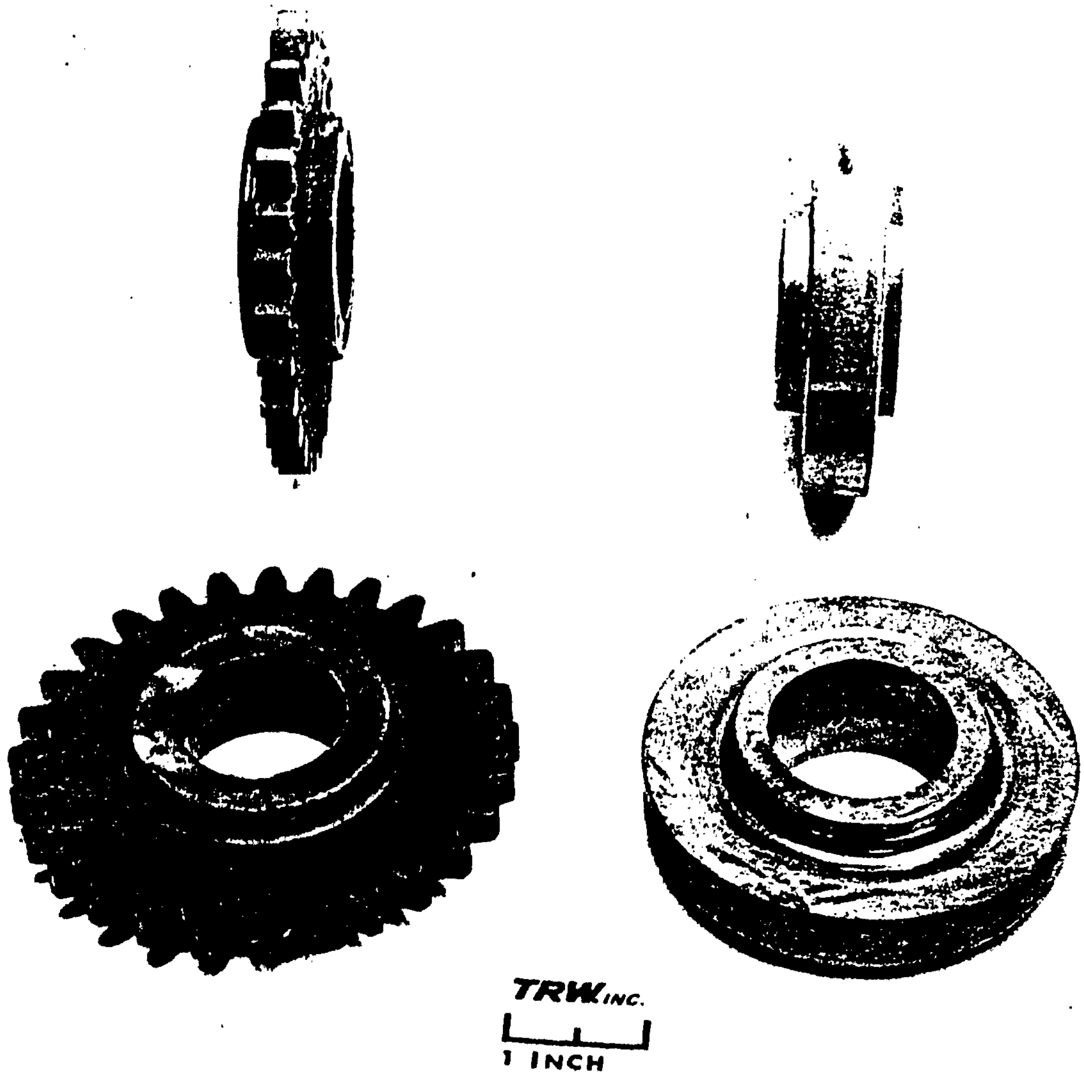
Figure 5-11. Lap Formation (Resulting from a Nonuniform Preform Density) on Hubs of P/M Forged Gears.

Individual green compacts were charged at ten-minute intervals into the furnace for sintering/preheating. After a thirty-minute dwell at 2200°F (1204°C), the preforms were transferred manually to the die cavity and forged in one blow to full shape and full density. Upon ejection, the gear was quenched in oil to a handleable temperature, and the core rod cap was removed. The core rod cap was inspected and reused. In between forging blows, the dies were wiped to remove excess graphite lubricant, and torch-heated to maintain temperature. The cartridge heaters were on continuously to help maintain a uniform die temperature. Just prior to forging, the die cavity, the bottom punch face, and the top punch face were sprayed with the graphite lubricant. After the batch of oversize gears were forged, they were normalized at 1650°F (900°C) for two hours and slow-cooled under a dissociated ammonia atmosphere.

A preform and forged gear is shown in Figure 5-12. This gear is in the as-forged condition with flash removed. Although trapped die forging is referred to as flashless forging, some flash in the form of vertical fins does form between the punches and ring die. The extent of flash is a function of the preform weight in comparison to the die cavity size, the temperature, the clearance gap between the punches and die, and the lubrication. The fins were removed by hand filing.

Several of these gears were sectioned and examined metallographically. As expected, the last regions to densify were the tooth tips where die wall contact is last made. In Figure 5-13, the tooth tip for a forging with incomplete die fill is shown. Residual porosity is evident at both the tip and the end of the tooth face, being most concentrated at the tip corner. For a fully formed gear tooth, some residual porosity is present at the tooth tip, as shown in Figure 5-14. This porosity is extremely difficult to eliminate. Because it does not affect the performance of the gear, it is not necessary to try to eliminate this trace of porosity; the critical regions of the gear tooth, the face, and the root are free of porosity. A typical tooth face is shown in Figure 5-15 in the as-polished condition. No porosity is evident. Examination of the microstructure in the etched condition revealed the presence of two types of inclusions. Metallic inclusions are shown in Figure 5-16. These are rich in nickel and probably stem from the original melt practice. In Figure 5-17, clusters of fine nonmetallic inclusions can be seen. These clusters are silicon-containing compounds, as revealed by the X-ray analysis shown in Figure 5-18. These inclusions also originate in the melt practice used for powder production.

Based on the outcome of these oversize gears, a set of punches and a ring die were machined by wire EDM for forging net gears. The room temperature dimensions of the ring die are given in Table 5-3. The forging conditions for achieving net teeth were as follows.


TRW INC.
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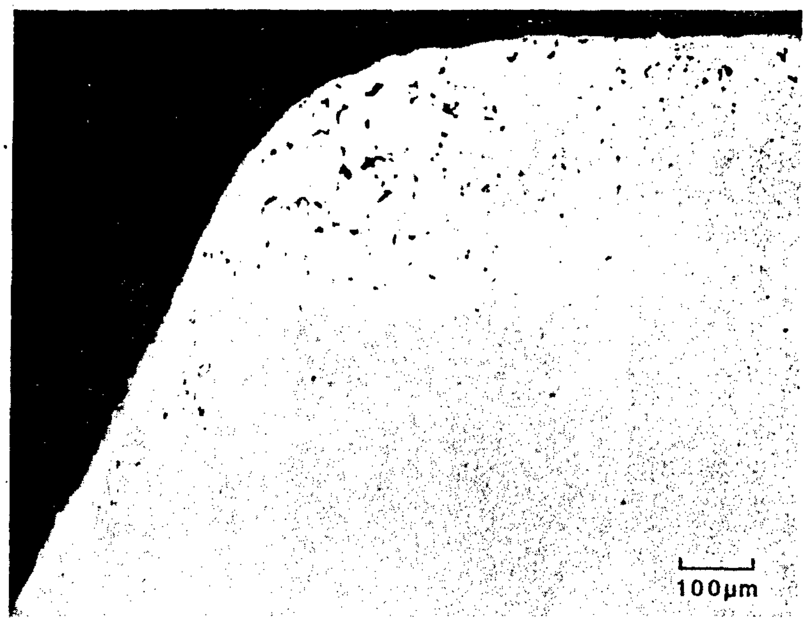
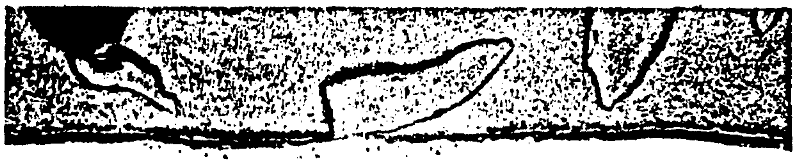
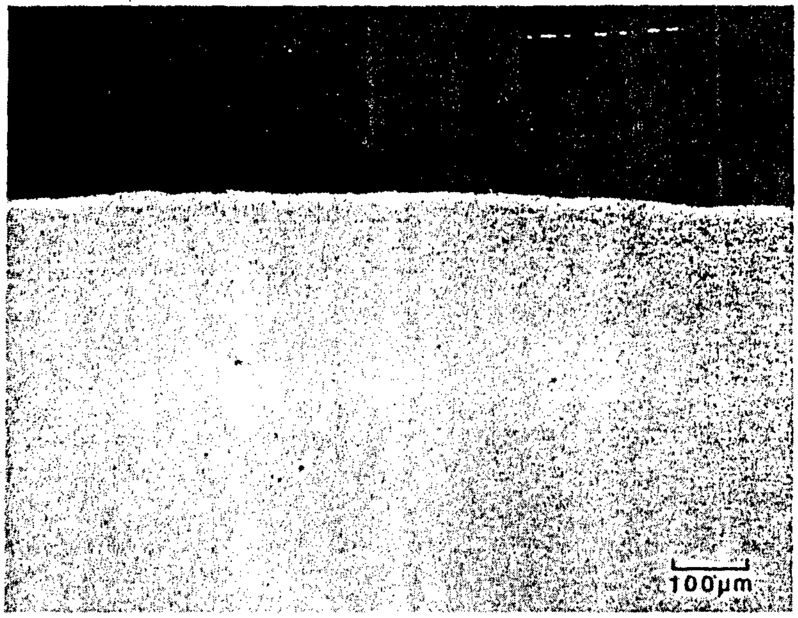
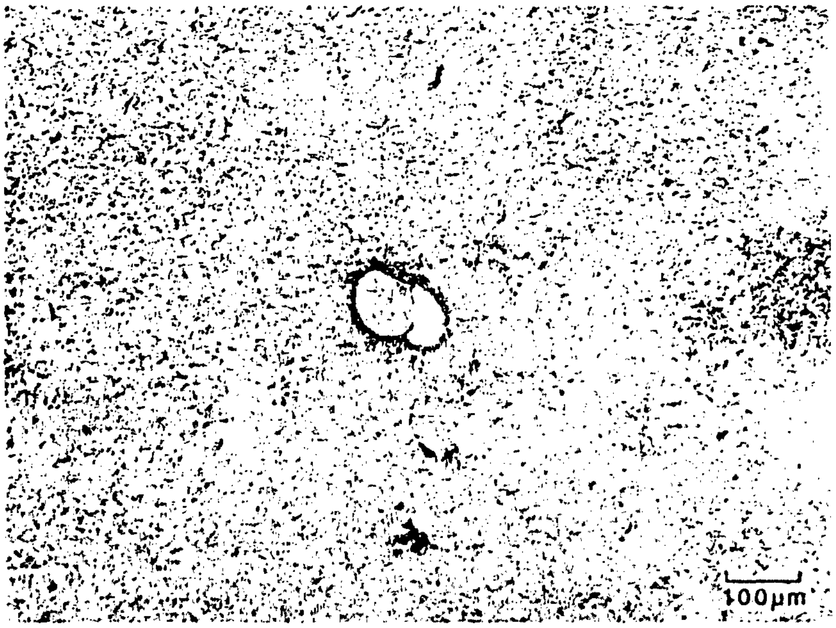


Figure 5-13. Residual Porosity in Underfilled Gear Tooth.

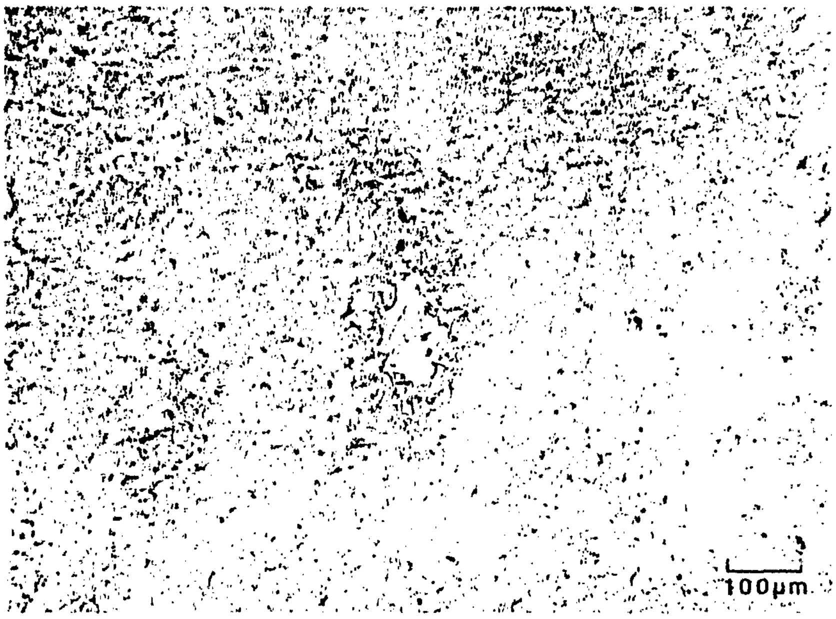


100µm


100μm

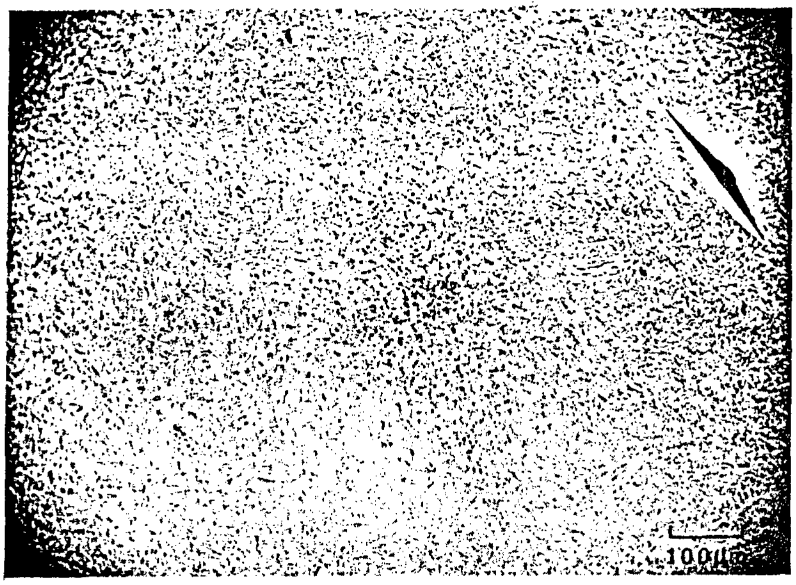


(a)

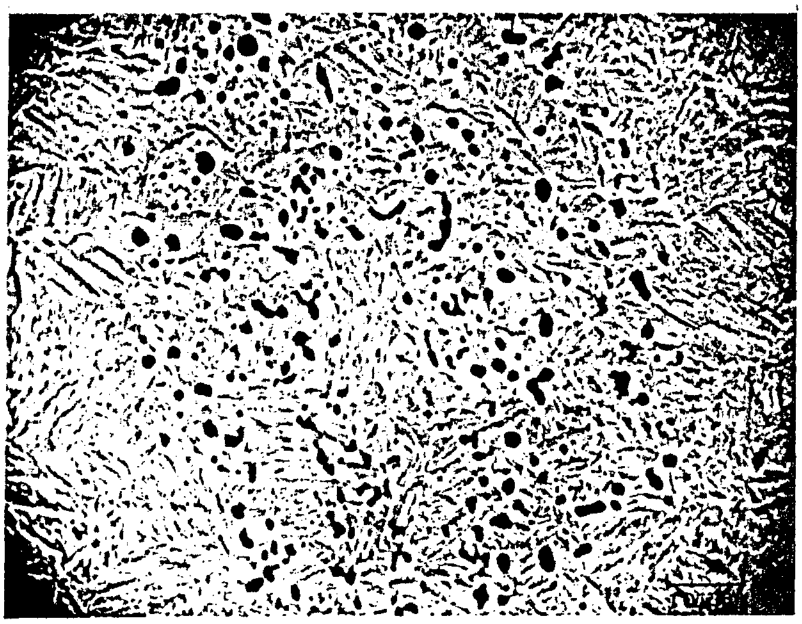


(b)

Figure 5-16. Examples of Metallic Inclusions in P/M Forged Gears.



(a)



(b)

Figure 5-17. SEM Micrographs of Nonmetallic Inclusion Clusters in a P/M Forged 4620 Gear.

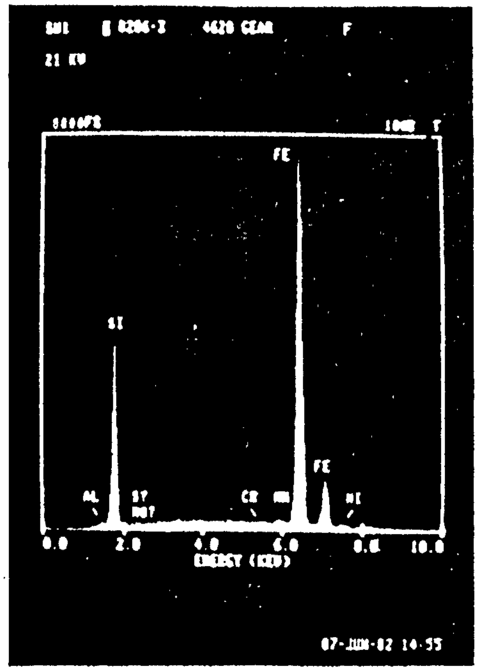


Figure 5-18. X-Ray Analysis of Nonmetallic Inclusion Clusters Shown in Figure 5-17.

TABLE 5-3. Dimensions of NASA Test Gear Die Cavity for Forging of Gears with Net Teeth.*

Number of Teeth	28
Diametral Pitch	8
Circular Pitch	0.396 in.
Chordal Tooth Thickness (Ref.)	0.193 in.
Pressure Angle	20^{o}
Pitch Diameter	3.533 in.
Major Diameter	3.786 in.
Minor Diameter	3.174 in.
Root Fillet Radius	0.060 in.
Tip Radius	0.010 in.

* Punches have a 0.002 in./0.004 in. clearance gap per side.

- o die temperature of 355 to 385°F (180° - 196°C)

- o preform preheat temperature of 2200°F (1204°C) with a 30-minute sintering/heating time

- o A transfer time of four seconds.

The processing window for achieving net teeth was found to be tight. Die temperatures above 385°F (196°C) or slow transfers (4 sec.) produced oversize forgings. Die temperatures below 355°F (180°C) produced undersize forgings. Because four seconds was the practical lower limit on transfer time, excessively fast transfers did not occur. If they had, undersize forgings would have resulted. One other facet of die temperature was die fill and chill. The lower limit seemed to be 350°F avoiding gross die chill on gear teeth and for achieving full cavity fill. A series of forgings of 4620 and 4640 steel powder were produced using these conditions. These forgings were normalized following the same cycle described above.

5.1.3.4. Finishing of Test Gears. Some finishing of these gears was necessary prior to testing. Because of the high Hertzian stress level of the NASA gear test, all gears were carburized prior to any finish machining. Oversize gears were sized by grinding. All gears were forged with undersize bores. Because of the concentricity requirements for these gears, wire EDM was used to cut the bore and key slots after heat treatment and any required tooth finishing. This produced acceptable concentricity between the gear dimensions and the bore.

The 4620 and 4640 gears were carburized according to the cycle presented in Table 5-4. Prior to carburizing, all surfaces except the gear tooth faces were coated with a carburizing stopoff compound to limit carburizing to the gear teeth. The microhardness profile produced by this carburization cycle is tabulated in Table 5-5 for a 4620 gear. The actual hardness level of Rc 58-59 is below the aim hardness of Rc 60-62. The effective case depth was determined by the heat treater (0.038 inches), and the surface hardness (Rc 60). This case depth was sufficient to allow subsequent tooth grinding where necessary. A micrograph of a typical gear tooth is shown in Figure 5-19.

The oversize gears were then machined by grinding after carburizing.

5.1.4. Gear Testing at NASA Lewis Research Center. Gears were tested at NASA Lewis Research Center under the direction of Mr. Dennis Townsend. A set of gears prior to delivery to NASA is shown in Figure 5-20. A complete report of gear test results is found in NASA Report. Some of the test details and results are summarized in the following paragraphs.

TABLE 5-4. Carburizing Cycle for P/M Forged NASA Test Gears

STEP

1. Carburize at 1650°F to an effective case depth of 0.033 in. at a carbon potential of 0.85-1.0 percent. The aim surface hardness is Rc 60-62.

2. Air Cool

3. Stress Relieve at 1200°F for 2.5 hrs.

4. Austenitize at 1550°F for 2.5 hrs. followed by an oil quench.

5. Deep freeze at -120°F for 3.5 hrs.

6. Double temper at 300°F for 2 hrs.

TABLE 5-5. Microhardness of Carburized Gear Tooth.*

Distance from Tooth Face (in.)	Hardness, Rc
0.0012	54.8
0.0052	59.1
0.0092	58.7
0.0132	58.0
0.0172	58.4
0.0212	57.7
0.0252	56.7
0.0292	54.8
0.0332	52.6
0.0372	51.8
0.0412	49.8
0.0452	48.3
0.0492	47.8
0.0532	47.2
0.0572	45.9
0.0612	45.4
0.0652	44.8
0.0692	44.8
0.0732	43.0
0.0772	44.2
0.0812	44.8
0.0852	44.8

* Taken approximately at the pitch diameter.

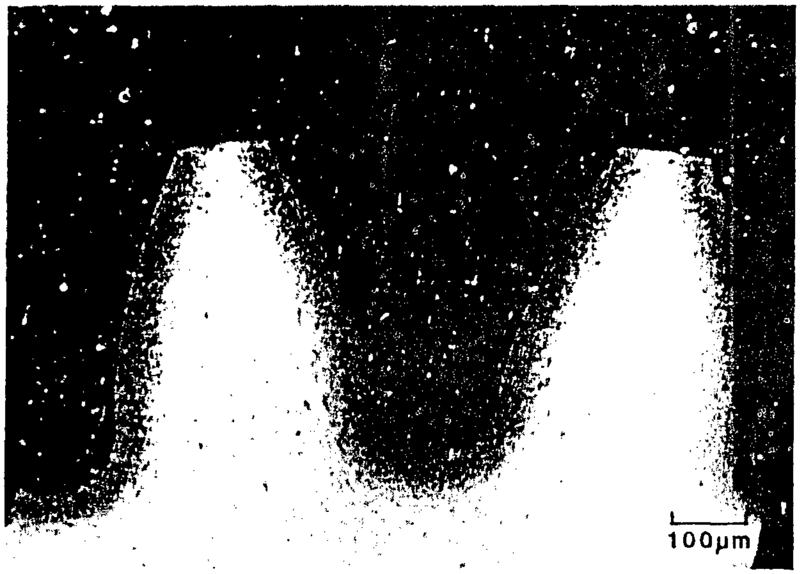


Figure 5-19. Macroetched View of P/M Forged 4620 Gear Showing the Carburized Case.

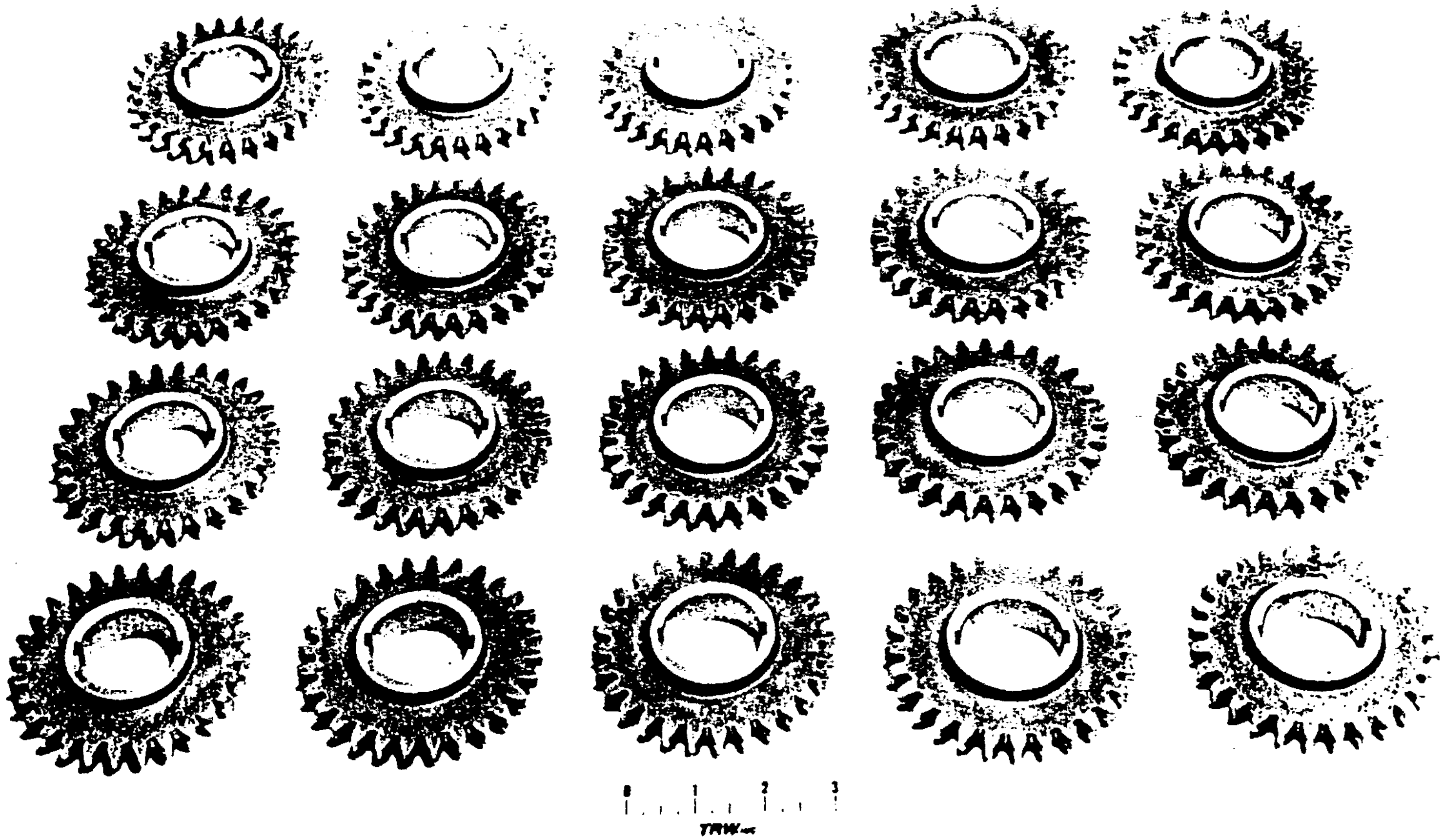


Figure 5-20. Set of P/M Forged 4620 Gears Ready for Rig Testing at NASA-Lewis Research Center.

The gears were tested at NASA in a four square test rig, shown schematically in Figure 5-21. The gears are offset from each other so that only one-half of the tooth face is loaded. This produces a complex stress state in the gear tooth which consists of bending and twisting. The gears turn at 10,000 rpm and a Hertzian stress of 248,000 psi is applied at the pitch diameter. The maximum bending stress is 37,000 psi. Data obtained from the test are cycles-to-failure, Wiebull plotting being used to evaluate data.

The data for 9310 steel gears, the standard material for helicopter transmission gears, and the data for the P/M forged gears of 4620 and 4640 steel powder, are shown in Figure 5-22. The baseline gears of 9310 steel have a B10 life of $8x10^6$ cycles. P/M forged 4620 gears which were carburized and finish ground and a B10 life of $13x10^6$ cycles. P/M forged 4620 gears which were carburized only (no grinding or finishing operatins on gear faces) had a B10 life of $5x10^6$ cycles.

The data shown in Figure 5-22 are encouraging. First, for this highly loaded test case, P/M forged gears with ground teeth show potential for replacing the 9310 alloy gears. The P/M forged gears have a slope similar to the baseline gears. While they have a lower B10 life, they also have a lower surface hardness, which, coupled with their lower alloy content, may explain the differenct in B10 lives. Second, P/M forged gears with net tooth faces exhibit scatter which is most likely due to the dimensional variations of forged plus heat-treated surfaces. These variations are magnified at this high level of loading. For more moderately loaded gears, as-forged surfaces would be acceptable, as has been shown for studies involving automotive gearing applications (Ref. 2,3). Third, no P/M forged gears suffered tooth breakage during testing. Failure occurred by spalling and cracking along the highly loaded tooth faces. The beneficial effect of metal flow during forging prevented tooth breakage. Gears machined from 4340 bar, on the other hand, did experience tooth breakage. The original mechanical fibering in the bar is still present in machined and heat-treated gears. The orientation of this fibering provides crack paths to promote tooth breakage.

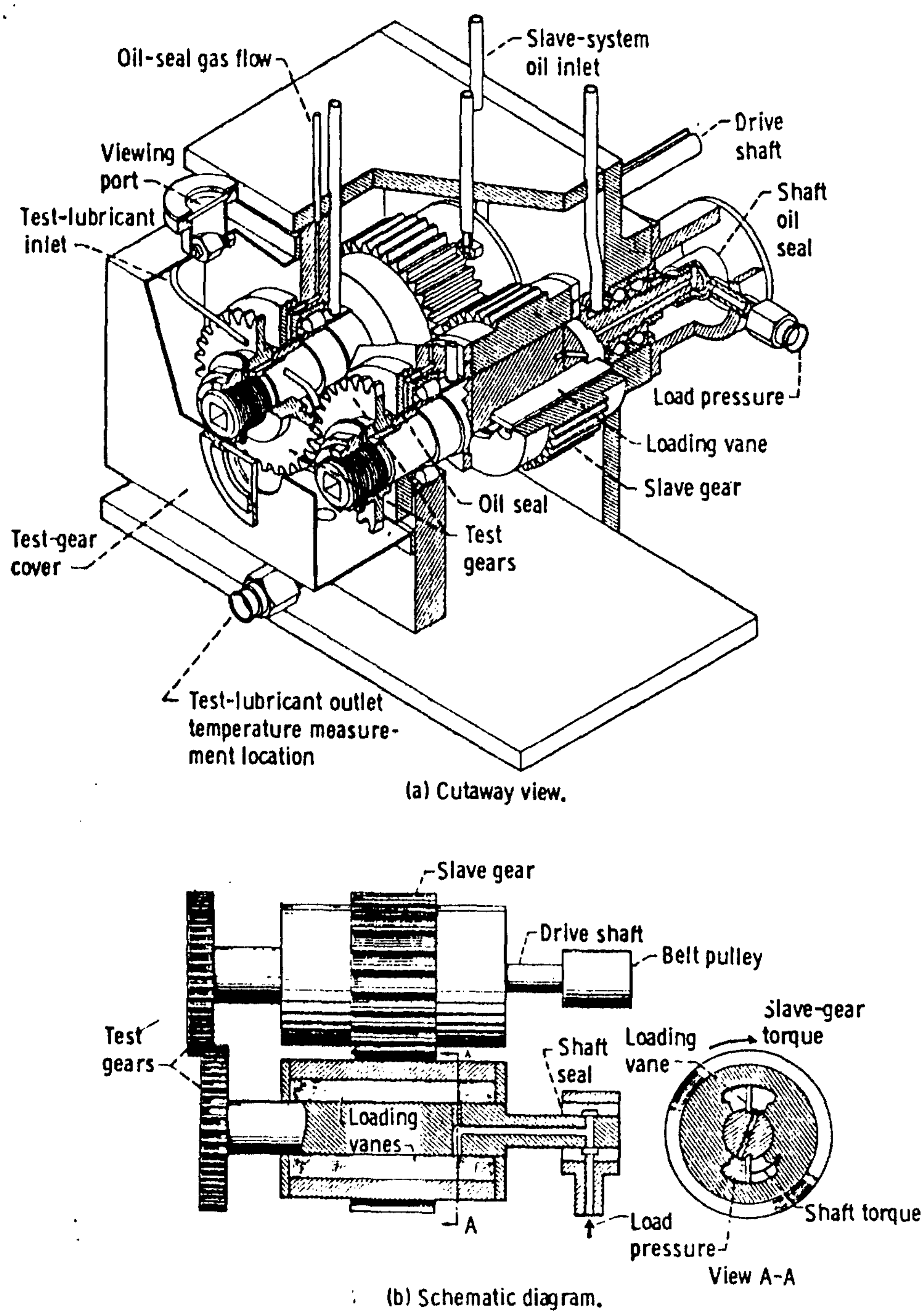


Figure 5-21. Schematic of 4-Square Test Rig at NASA-Lewis Research Center.

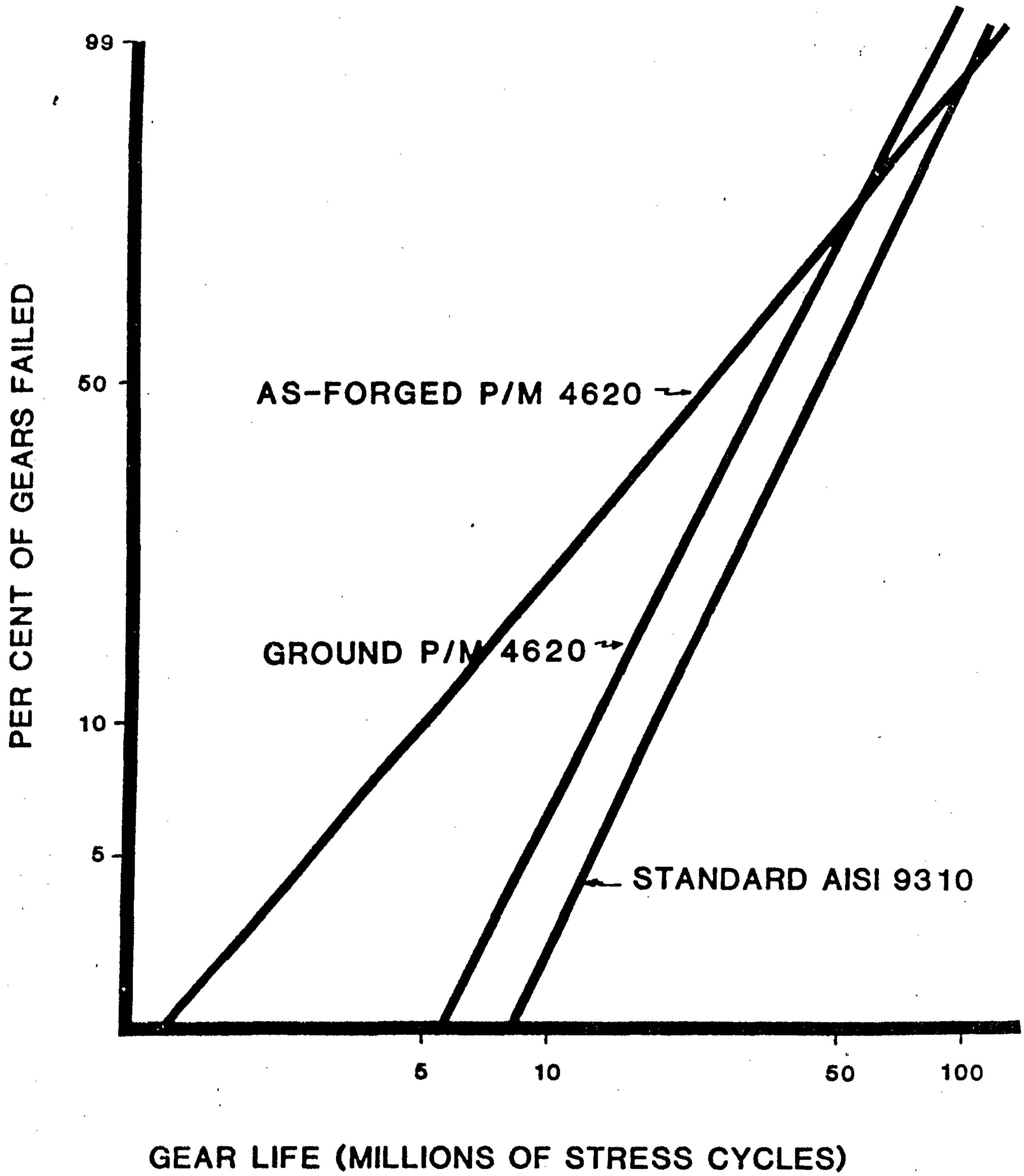


Figure 5-22. Weibull Plot of Gear Test Data.

5.2. AGT 1500 Turbine Engine Accessory Gears (Phase II)

Phase II of this project was aimed at implementing the technology gained in Phase I for P/M forging accessory gears in the AGT 1500 turbine engine used in the Abrams Tank. The No. 6 gear of the accessory gear box was selected as a candidate for P/M forging. This gear is shown in Figure 5-23, and the gear tooth data are tabulated in Table 5-6. The current method of manufacturing this gear is by machining aircraft quality 4340 bars. The gears are used in the through-hardened condition, at a hardness level of Rc 34 to 37.

5.2.1. Experimental Program. The material selected for forging these gears was 4640 steel powder. Preform stock was produced by cold isostatically pressing (CIP) a log of powder in urethane tools at a pressure of 60,000 psi (414 MPa), followed by sintering at 2200°F (1204°C) for one hour in a dry hydrogen plus 1 volume percent methane atmosphere. Preforms were than machined from this sintered log.

Two preform geometries were initially considered for forging these gears. These geometries, shown in Figure 5-24, were selected to examine differences in lateral flow during forging. The gears have very fine teeth, and tooth cracking during forging was anticipated to be a major problem.

The forge tools for producing these gears are shown in Figure 5-25, and the die dimensional data are given in Table 5-7. The die cavity and punch teeth were machined by wire EDM, with a clearance of 0.004 inches per side between the punches and die. Notice that the core rod has been incorporated into the top punch; this was done to facilitate ejection.

Seven trial forgings were performed using preform preheat temperatures from 1800°F to 2200°F (982°C to 1204°C). The density of these preforms was 86 percent of theoretical, which was greater than the design density of 80 percent. The top preform in Figure 5-24 was used for these trials, with the weight reduced to"1.4 inches to assure that the die cavity would not be overfilled. The die and punches were heated to 500°F (260°C) for these trials. Results are tabulated in Table 5-8. Figure 5-26 shows the forged gears. Ejection proved to be a problem, as indicated by the comments in Table 5-8. Manual ejection means that the forging cooled in the die until it could be manually extracted. This was possible since the core rod was part of the top punch and thus was pulled out of the gear as the crank returned to its upper position and thermal contraction of the gear resulted in sufficient shrinkage to separate it from the die wall.

The forging loads reported in Table 5-8 are 1000 tons (8.96 MN) for the range of preheat temperatures examined. Die fill was complete in

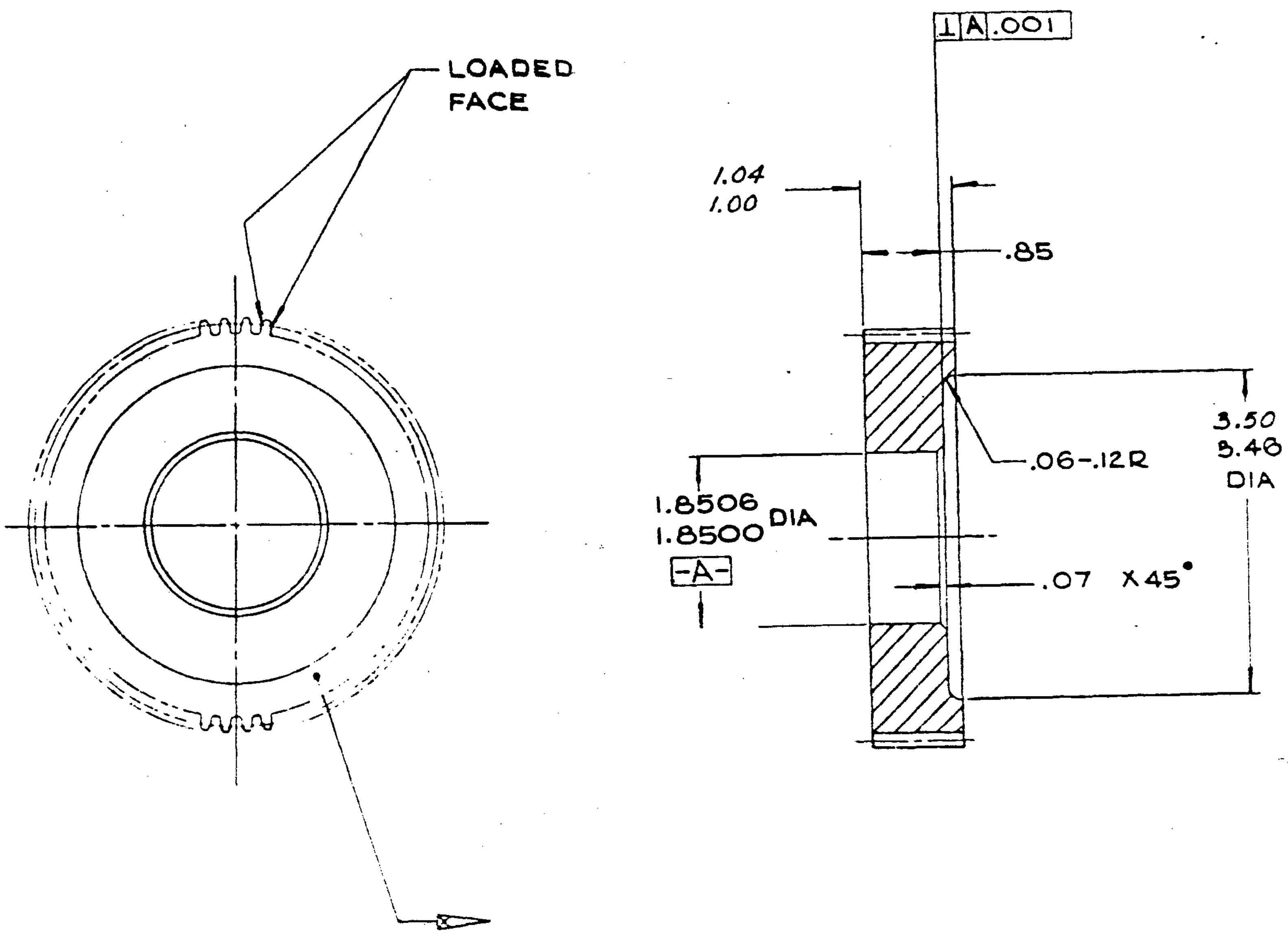


Figure 5-23. AGT 1500 No. 6 Accessory Gear.

TABLE 5-6. Gear Data for AGT 1500 No. 6 Accessory Gear*

Number of Teeth	61
Type of Fillet	Full
Diametral Pitch, Rolling	14.000
Pressure Angle, Rolling	20.000 deg.
Outside Diameter	4.495 in.
Pitch Diameter, Rolling	4.3571 in.
Base Circle Diameter	4.0944 in.
Form Diameter, Max.	4.2393 in.
Root Diameter	4.15 in
Circular Tooth Thickness	0.1057/0.1087 in.
Root Fillet Radius, Min.	0.030 in.
Backlash with Mating Gear	0.006/0.014 in.
At Center Distance	5.9633/5.9353 in.
Diameter of Measuring Wires	0.144 in.
Measurement Over Wires	4.5882/4.5954 in.
Number of Teeth in Mating Gear	83, 106
Part No. of Mating Gears	3-080-079-01 3-080-078-01

* 1 inch equals 0.025 m.

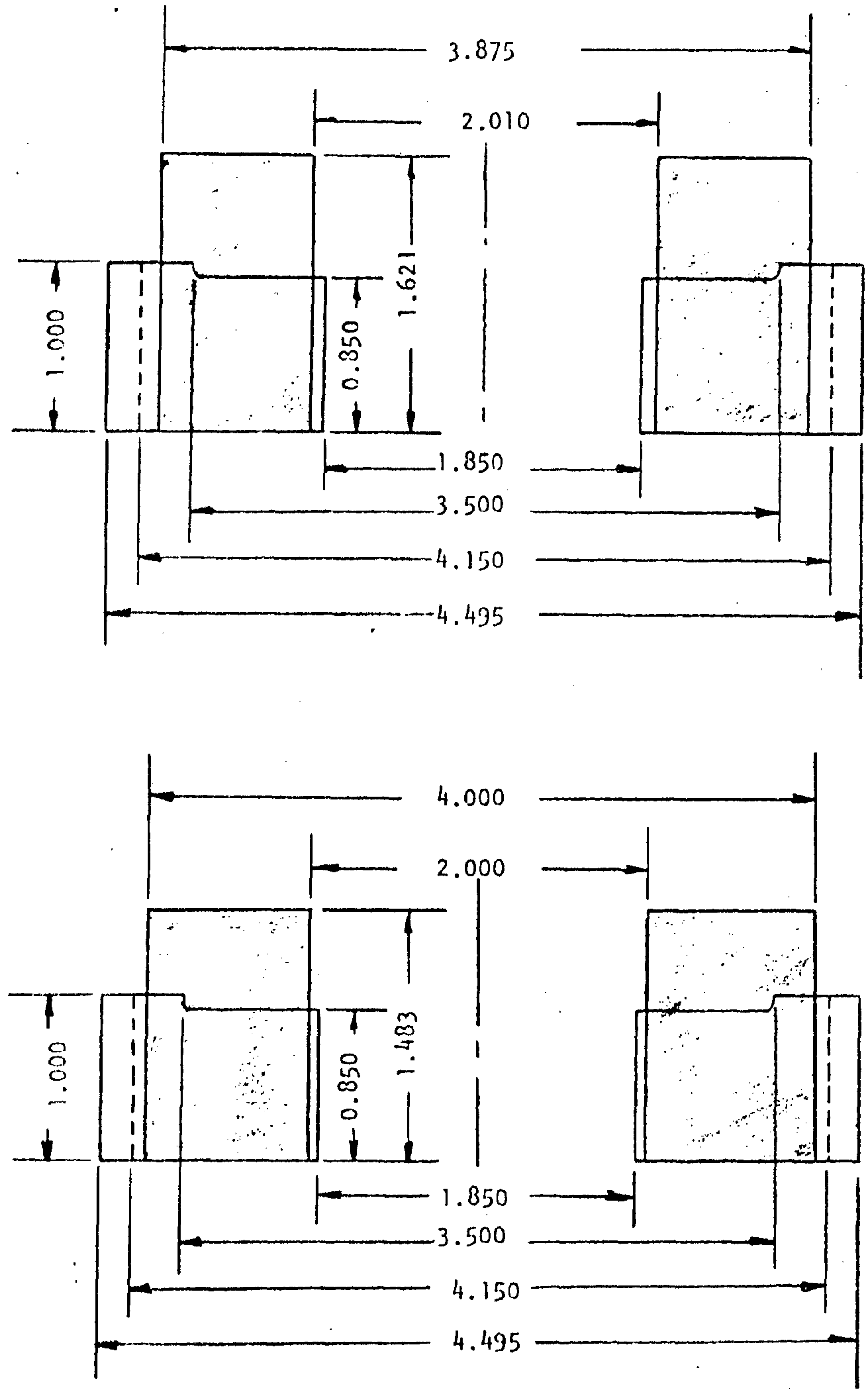


Figure 5-24. Schematic of Possible Preform Shapes (80% Density) and Forged Shapes for P/M Forging of No. 6 Accessory Gear in AGT 1500 Turbine.

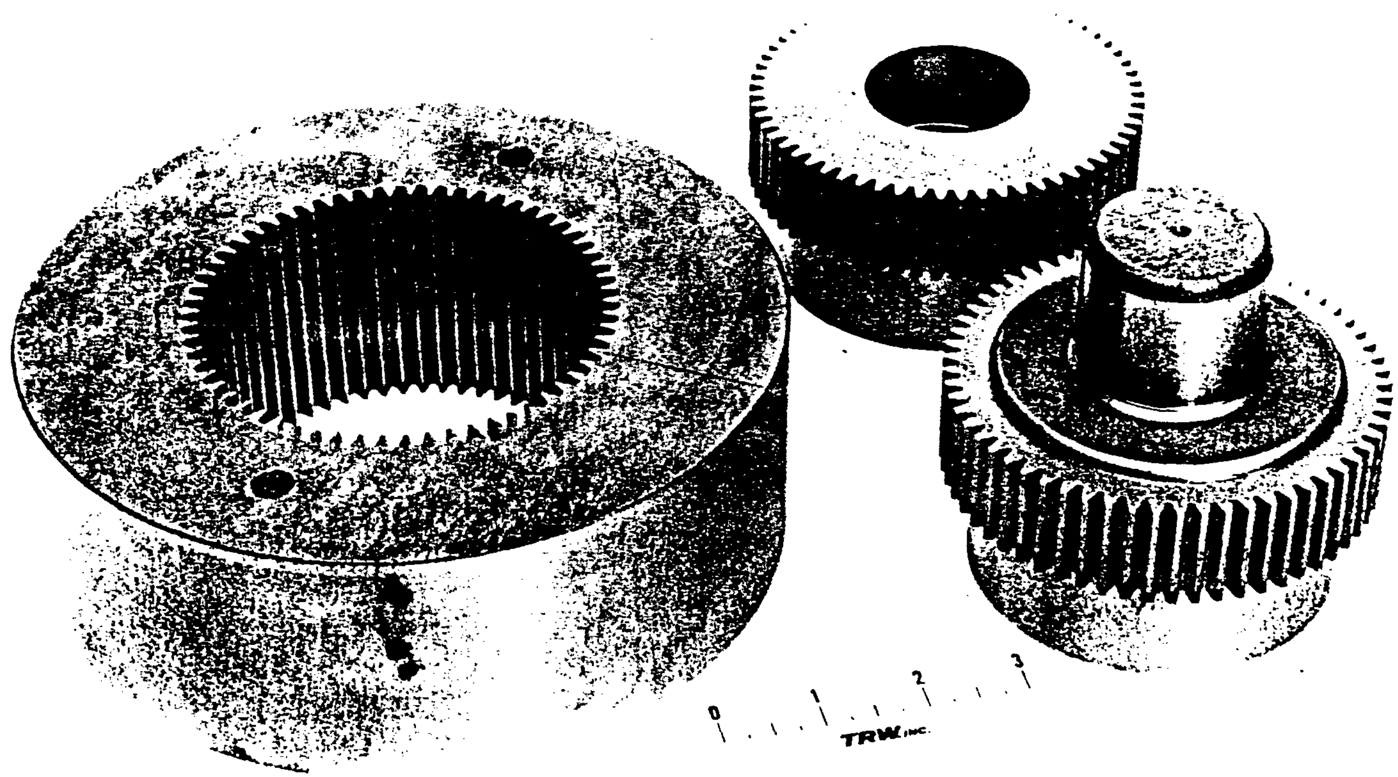


Figure 5-25. Forging Tooling for AGT 1500 No. 6 Accessory Gear.

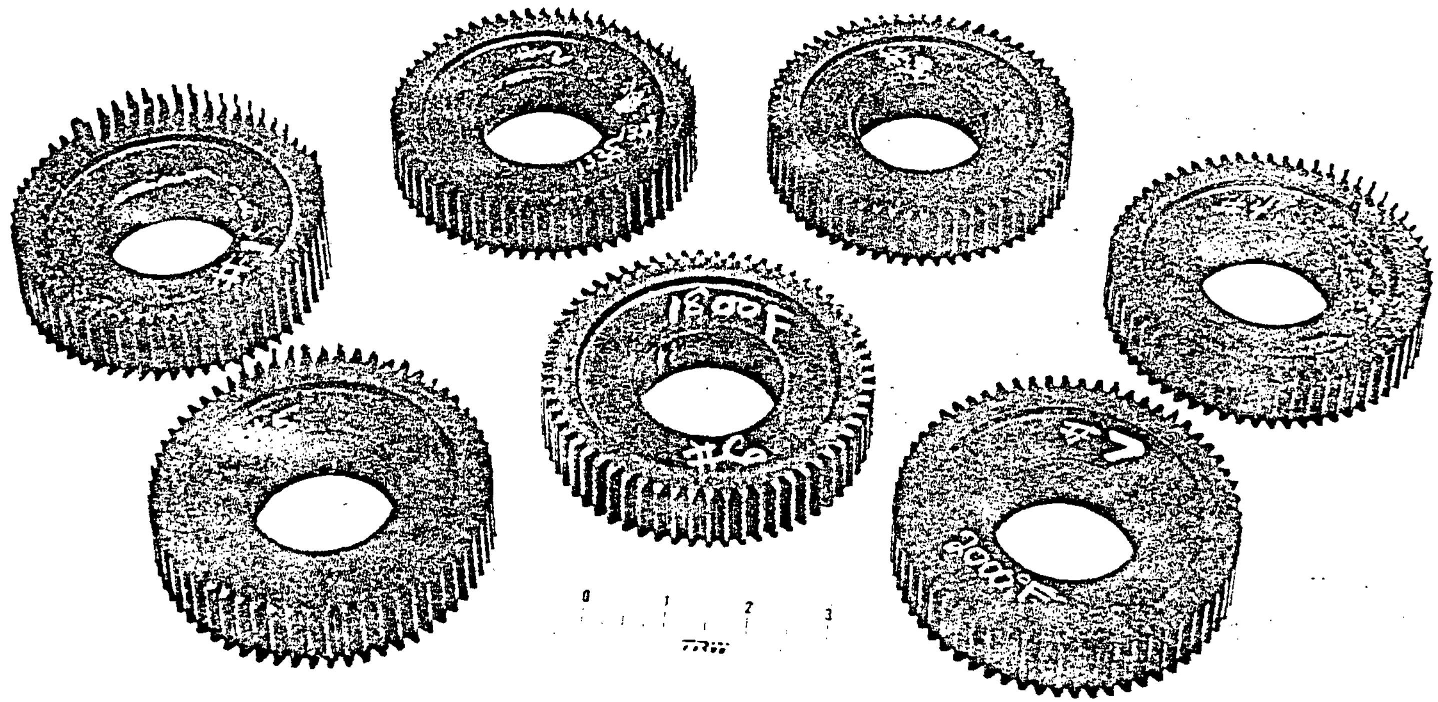


Figure 5-26. Trial Forgings of AGT 1500 No. 6 Accessory Gear For a Preform Preheat Temperature Range 1800° to 2200°F.

all cases except in the trial at 1800°F (982°C). Flash formed on both lower and upper faces at the punch/die gap. The trial at 1800°F (982°C) produced the best surface finish.

Measurements of these gears, as shown in Table 5-9, revealed two problems. First, the bottom diameter measurements, made over pins, exceeded the top diameter over-pin measurement values by 0.01 inches (0.25 mm). Second, a thickness taper of the same magnitude was present. It is believed that the first problem caused the ejection problems. The reason for this locking type taper was proposed to be the die heating method. As shown in Figure 5-27, torch heating of the accessory gear tooling may have heated the bottom punch and lower part of the ring die to a greater temperature than the upper part of the ring die since the flame was trapped in the core rod cavity of the bottom punch. Use of a lower core rod would not have solved this problem as the core rod would deflect and spread the flame. Based on the thermal expansion coefficient of H-13 tool steel (6.6×10^{-6} inch per inch per fahrenheit), a 0.01 inch (0.25 mm) taper could be produced by a top-to-bottom temperature difference of 335°F (170°C). This would not only make the part lock in the ring die, but the bottom punch would also lock and resist upward motion. Subsequently, a pancake piece was used to deflect the torch flame for even tool heating. While the ejection problem ended,the part taper was not eliminated.

A problem concerning response to heat treatment and carbon control unexpectedly arose during this phase of the program. Attempts to harden 4640 gears resulted in extremely soft gears. Metallographic examination showed excessive decarburization. Gears of 4660 composition were forged, and these also had decarburization and corresponding low hardness. The decarburization could be remedied by carburization. The likely explaination was attributed to a small water leak in the jacket of the cooling chamber. The decarburization was most likely caused by high moisture content in the furnace. Because hardness is related directly to gear performance, this problem of carbon control was a major concern.

5.2.2. Forging of Accessory Gears. Forging of accessory gears for delivery to TACOM for testing and inspection was performed using a preform preheat of 2200°F (1204°C), a die temperature of 450°F to 500°F (232°C to 260°C), Deltaforge 33 as the die lubricant and preform coating, and a transfer time of four to five seconds. With the pancake cover present during torch heating, a top-to-bottom taper of the forged gear was still present, although no ejection problems were encountered. A set of 12 gears of 4640 composition were produced. These are pictured in Figure 5-28, and dimensional data are contained in Table 5-9.

The dimensional data verify the presence of tapers on the diameter and the thickness. Also, the measurements over the pins fall below the

TABLE 5-7. Die Cavity Dimensions to Forge AGT 1500 No. 6 Accessory Gear

Number of Teeth	61
Diametral Pitch	14
Circular Pitch	0.228 in.
Circular Tooth Thickness (Ref.)	
Pressure Angle	20.0°
Pitch Diameter	4.377 in.
Major Diameter	4.505 in.
Minor Diameter	4.160 in.
Root Fillet Radius	0.030 in.

TABLE 5-8. Forging Trials for AGT 1500 No. 6 Accessory Gear

Preform		Temperature, F		Forging	
No.	Weight (g)	Preform	Die	Load (t)	Comments
1	1348.4	2200	490	1016	- heavy flash - slow ejection
2	1337.6	2200	500	1003	- manual ejection
3	1338.4	2200	450	1013	- slow ejection
4	1323.0	2200	460	916	- manual ejection
5	1338	2200	500	997	- manual ejection
6	1333	1800	500	945	- manual ejection
7	1340	2000	500	977	- manual ejection

TABLE 5-9. Dimensional Data for Accessory Gear Trial Forgings*

Gear No.**	Measurement Over Pins: Top Dia.	Measurement Over Pins: Mid. Dia.	Measurement Over Pins: Bot. Dia.	Bore Dia.	Part Height
1	4.567	4.571	4.578	1.842-1.845	0.968-0.981
2	4.571	4.579	4.582	1.844-1.846	0.964-0.977
3	4.570	4.575	4.582	1.850-1.853	0.970-0.975
4	4.564	4.571	4.577	1.845-1.848	0.958-0.962
5	4.572	4.576	4.582	1.846-1.850	0.964-0.975
6	4.584	4.590	4.595	1.853-1.856	0.954-0.966
7	4.579	4.586	4.589	1.849-1.852	0.965-0.970

* Dimensions are in inches.
** Gear No. is same as Preform No. in Table 5-8.

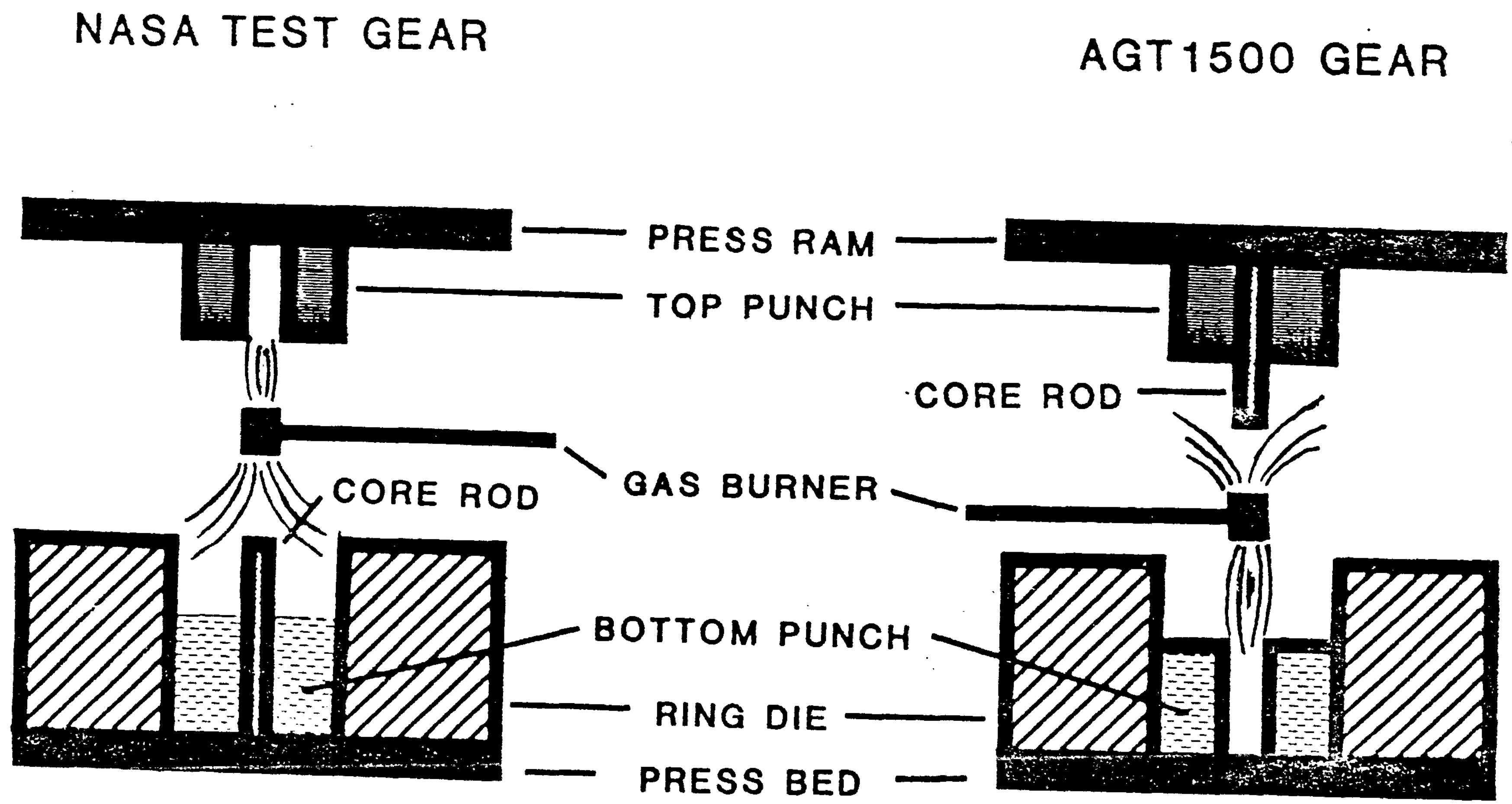


Figure 5-27. Comparison Between Tooling Approaches for the NASA Test Gear and AGT 1500 No. 6 Gear.

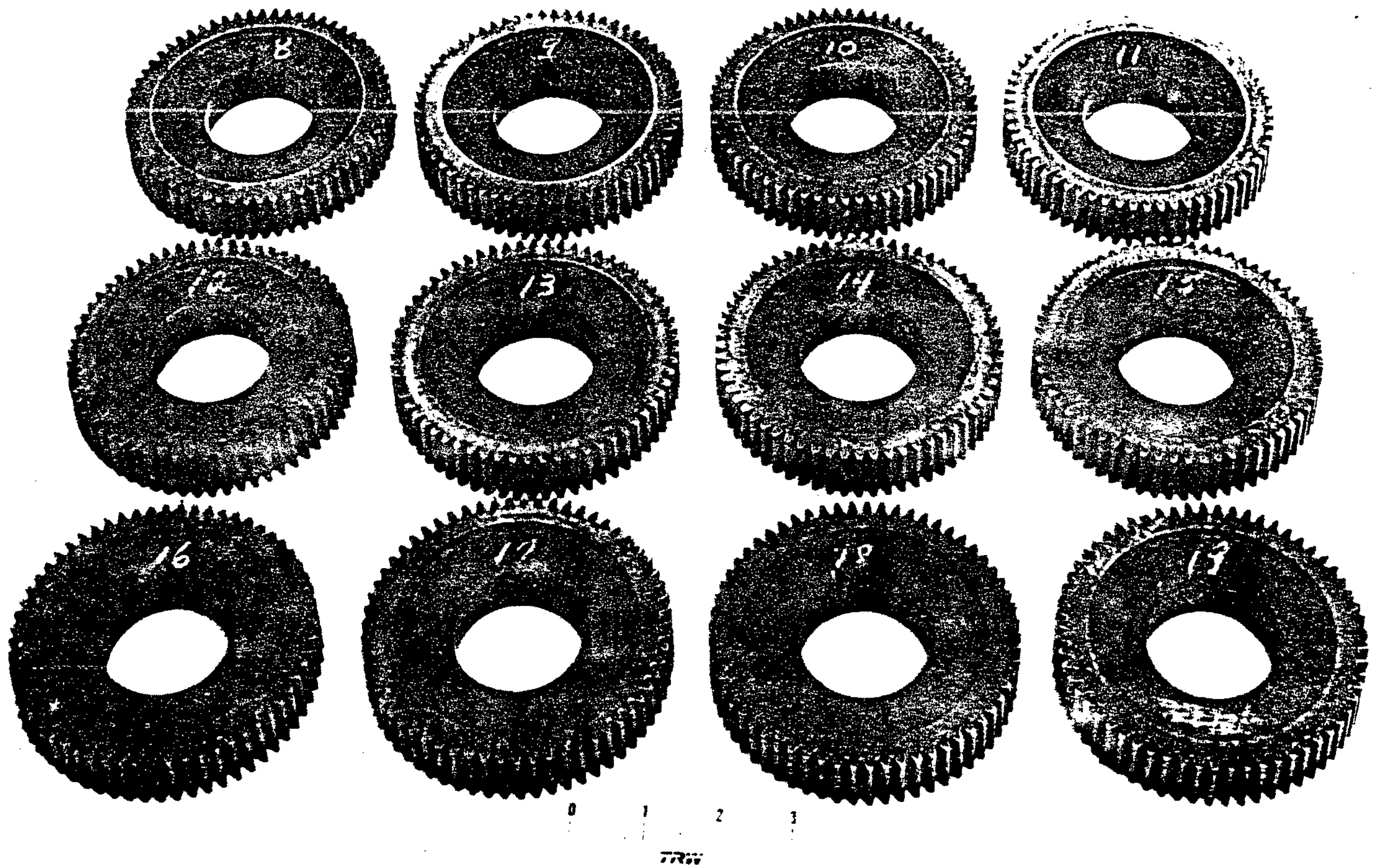


Figure 5-28. As-Forged AGT 1500 No. 6 Accessory Gears Forged From 4640 Steel Powder.

specified values in Table 5-6. This, in itself, is not a major problem, as a change in forging variables can bring the forgings into tolerance. The thickness taper was found to be consistent from part-to-part, being highest at a 10 o'clock position on the gear, relative to the die, and lowest at a 4 o'clock position. There are a few possible reasons for this taper,all of which suggest the need for press or die set modifications or adjustments. First, the bottom punch, which seats indirectly on a taper plate, may not be perpendicular to the ring die walls. For this to be true, there would be also problems in raising and lowering the bottom punch. This possibility has some merit because of the various ejection problems encountered. However, the bottom punch under normal operating conditions was not hindered during movement in the ring die. Other possibilities include a taper on either the top ram or the bed of the press, a shift in the ram under load, off-center alignment of the top punch and the press bed, and deformation of the bolster plates supporting either the top punch or the bottom punch. Of these possibilities, the most likely candidate is a shift of the ram under load. This could be due to an off-center situation, either by the piece being forged or by the punch alignment with the press bed, or by play in the ramguides and bearings.

Because of unexpectedly lower hardness (RA 45-47) observed in the representative 4640 powder forged gear, surface decarburization was suspected. The core hardness of a forged P/M 4640 gear in the fully hardened condition (i.e., austenitized at 1500°F (815°C) for one hour, quenched in oil, and double tempered at 475°F (246°C) for two hours) was in the Rc 20 range. The subsequent carbon analysis of this gear indicated that only 0.126 percent carbon was present. Therefore, decarburization along with a lower than critical cooling rate necessary for full hardening appeared to result in lower hardness in the powder forged 4640 gears. The decarburization appeared most likely to be caused by a high moisture content in the furnace.

While the carbon content of a steel determines the maximum hardness in the fully hardened condition, the alloying elements establish the critical cooling rate for full hardening and, therefore, the section thickness that can be hardened fully. For instance, for 4620 steels, the size of round that will through-harden in oil is 0.2 inch and the critical cooling rate at 1300°F is 305°F/sec. Therefore, the large section size (i.e., 1 inch) of the 4640 powder forged gears may have been partly responsible for slowing down the reaction rates and forming other structures (ferrite, pearlite, and upper bainite)than the fully hard structure (martensite). A water-quenching experiment showed that the core hardness of a 4640 forged gear could be raised to Rc 42. However, there is the distinct danger of distorting or even cracking the gears if they are quenched drastically enough to harden completely.

A new batch of quench oil (Bedcon K-9) was procured for the subsequent oil quenching operation. To replace gears which suffered from the loss of the carbon content during preheating to the forging temperature, five additional gears of a 4660 composition were produced. After a full hardening treatment*, core hardness of a 4660 forged gear was Rc 50. The analyzed carbon content was 0.6 percent.

Because of difficulties experienced in controlling the carbon content and the subsequent hardness, modified hardening procedures were established to maximize the information on responses to various heat treating conditions.

They are described as follows:

A. Hardening Procedure of AGT 1500 No. 6 Gears

(Nos. 1 through 19 are 4640 gears)
(Nos. 21 through 24 are 4660 gears)

A.1. Gear Nos. 1, 5, 10, 15, 19.

A.1.a.: Normalize by heating to 1650°F, holding at heat for 1 hour and cooling in air to room temperature.
A.1.b.: Harden by heating to 1550°F, holding at heat for 1 hour and quenching in oil.
A.1.c.: Double temper by heating to 475°F, holding at heat for 2 hours, cooling in air to room temperature, reheating to 475°F, holding at heat for 2 hours and cooling in air.
A.1.d.: Pack carburize at 1700°F for 12 hours using charcoal provided and cool to room temperature.

A.2. Gear Nos. 2, 6, 12, 16, 22.

A.2.a. Same as A.1.a.
A.2.b. Harden by heating to 1550°F, holding at heat for 1 hour, and quenching in water.
A.2.c. Same as A.1.c.
A.2.d. Same as A.1.d.

* Full hardening treatment consists of:
1. Normalize at 1650°F (899°C) for 1 hour.
2. Austenitize at 1500°F (816°C) for 1 hour.
3. Quench in oil.
4. Double temper at 475°F (246°C) for 2 hours.

A.3. Gear Nos. 3, 8, 13, 17, 23.

A.3.a.: Same as A.1.b.
A.3.b.: Same as A.1.c.

A.4. Gear Nos. 4, 9, 14, 18, 24.

A.4.a.: Same as A.2.b.
A.4.b.: Same as A.1.c.

Of the 20 gears, three gears were given a through-hardening treatment and teeth were shaved at Midwest Gear Corporation, Twinsburg, Ohio, to meet the hardness (Rc 34-37) and dimensional requirements per drawing 3-080-076-01. The shaved gears should be appropriate for rig or engine testing. The above-described hardening procedure had been discussed and agreed upon with the TACOM responsible engineer. All 20 gears were subsequently delivered to TACOM for inspection and testing.

5.3. M2 Gear (Phase III)

The M2 personnel carrier manufactured by FMC Corporation contains many gears that potentially can be made at reduced costs by P/M forging. A ring gear, shown in Figure 5-29, was selected the the final phase of this program. Tooth data for this power take-off gear are contained in Table 5-10. P/M forging of ring shapes has been found to be an economical alternative to conventional forging and machining from either bar or tube stock. Therefore, this particular gear selection was justified on economic considerations alone. From a technical standpoint, the gear presented a challenge because of the thin wall and the size of the gear teeth. The preform for such a shape must be tall and thin, which causes handling and chilling problems, as well as the expected workability problems of a porous preform.

5.3.1. Die Design. Die design for the M2 gear was performed using CADAM and the equations discussed in Appendix B. Coordinate data in the form of NC tapes for the die cavity were determined by this approach, and these were used to machine the die cavity and punches by wire EDM. The die cavity form data are given in Table 5-11. Figure 5-30 shows the die cavity profile constructed by CADAM. This is the trace the electrode follows during wire EDM.

The die nest with M2 tooling in place is depicted in Figure 5-31; the tools are shown in Figure 5-32. As with the accessory gear, the core rod is a part of the top punch in order to minimize core rod-forging-contact time and to aid ejection. The tools were designed to operate at 450°F (232°C) to minimize die chill in this thin wall part.

5.3.2. Preform Design. Preform design for this gear faced two potential problem areas. First, the tooth length roughly equals the wall thickness of the part. This means that the lateral flow needed to fill the tooth is substantial in comparison to the overall lateral flow. Cracking on tooth tips is highly likely for such cases. Fortunately, the tooth thickness is fairly large, which helps to minimize diametral tensile strains. Second, this part has a high surface area-to-volume ratio, which indicates that chilling of the preform must be considered. Not only does this chilling promote residual porosity along die-contacted surfaces, but gross chilling in thin wall parts reduces their workability and leads to cracking. With these constraints in mind, two preform geometries were determined. These were basically two thin wall rings with similar volumes but different dimensions. Using software for axisymmetric shapes, the two geometries were determined to be as follows:

Preform 1: 3.5 inches OD x 2.875 inches ID x 0.814 inches high.

Preform 2: 3.393 inches OD x2.875 inches ID x 1 inches high.

Approximately 20 preforms of each type were produced from thick walled tubes produced by CIP.

5.3.3. Forging Trials. Forging trials were conducted for this gear to examine the effect of preform temperature on forging response for thin wall shapes. The tooling was heated to 450°F (232°C) while the preforms were heated to 2100°F (1150°C), 2200°F (1204°C) or 2300°F (1260°C). The preforms were machined from green CIP thick walled tubes of 4640 and 4660 compositions. Preheating served as the sintering step. Prior to preheating, the green preforms were sprayed with Deltaforge 33. This lubricant was also applied to the dies prior to forging.

Using a fiber optics probe, the temperature of the preforms was monitored during transfer from the furnace to the tooling. A drop of 300°F (150°C) occurred for each of the preheat temperatures, so the actual preform temperatures as they entered the forge die were 1800°F (982°C) to 2000°F (1093°C). Upon ejection, the gear teeth were already black, indicating that considerable chilling had occurred.

Cracking at tooth tips and die fill were in evidence for these forgings. Cracking and die fill were most prominent for a preheat temperature of 2100°F (1150°C). At the high preheat temperature, oxidation degraded the surface finish. For these forgings, 2200°F (1204°C) seemed to be a lower limit for preheat temperature and 2300°F (1260°C) was an upper limit. A trial at a preheat temperature of 2400°F (1315°C) caused the 4660 steel preform to sag. Because of chilling and poor surface finish, oversize teeth were forged to allow finish grinding.

TABLE 5-10. Gear Data for M2 Pinion Gear

EXTERNAL INVOLUTE SPUR GEAR DATA:

Standard Center Distance

Number of Teeth	31
Diametral Pitch	8
Pressure Angle.	20°
Minor (Root) Diameter	3.5548/3.5065
Measurement Over Two .216 Diameter Wires. . . . . (Optional Measurement of ARC Tooth Thickness)	4.1690/4.1618
Runout Tolerance Over .216 Diameter Wire to -B-	.0012 FIM
Profile Tolerance	See Chart
Lead Tolerance Across Face Width.	.0005
Pitch (Tooth to Tooth Spacing) Tolerance.	.0007

GEAR REFERENCE DATA:

Base Diameter	3.6413089
Nominal Whole Depth	.2938
Designed to Mate with Part Number	12276864
Operating Center Distance	6.8125
Operating Pitch Distance.	3.8750
Operating Pressure Angle.	20°

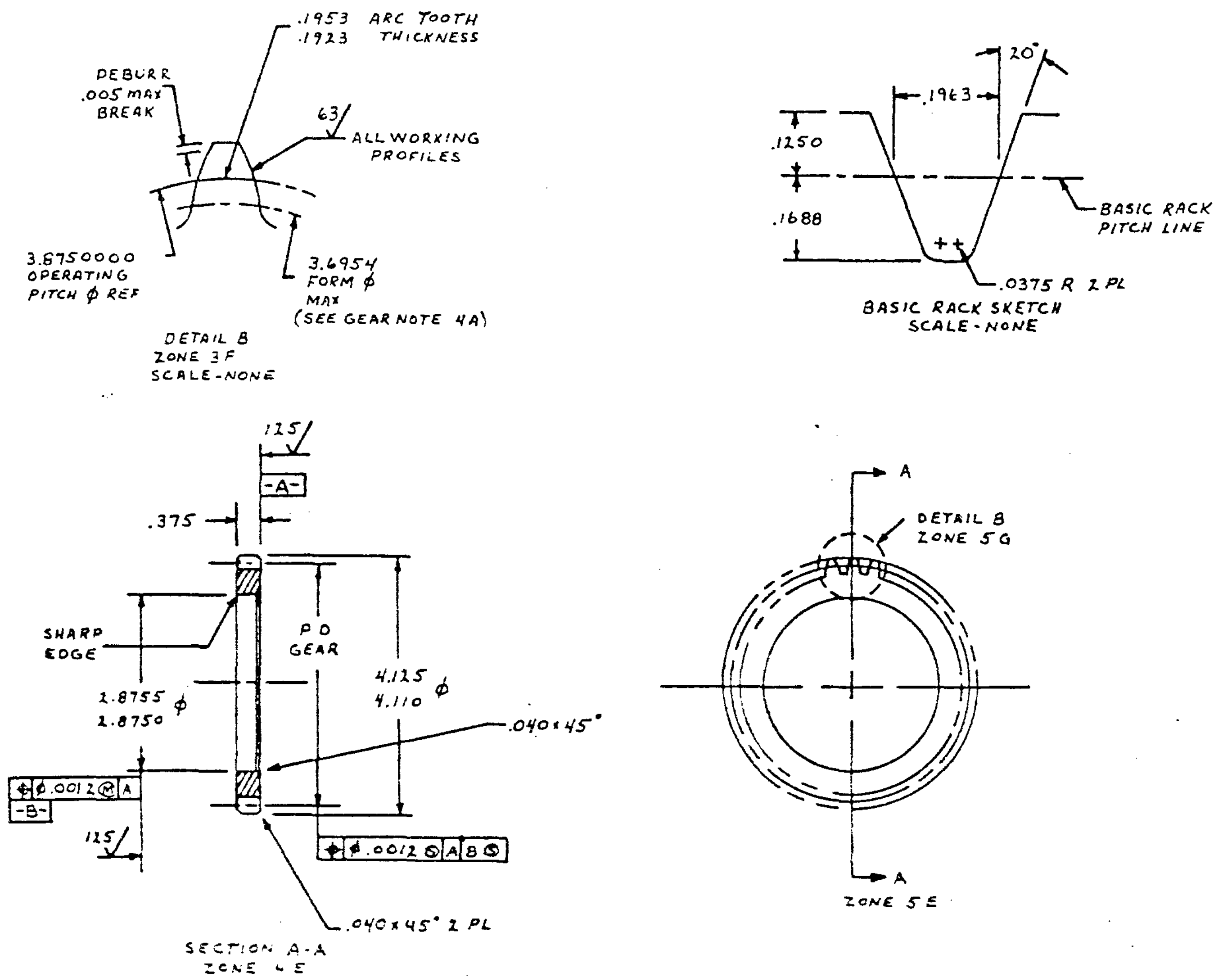


Figure 5-29. Pinion Gear for M-2 Personnel Carrier.

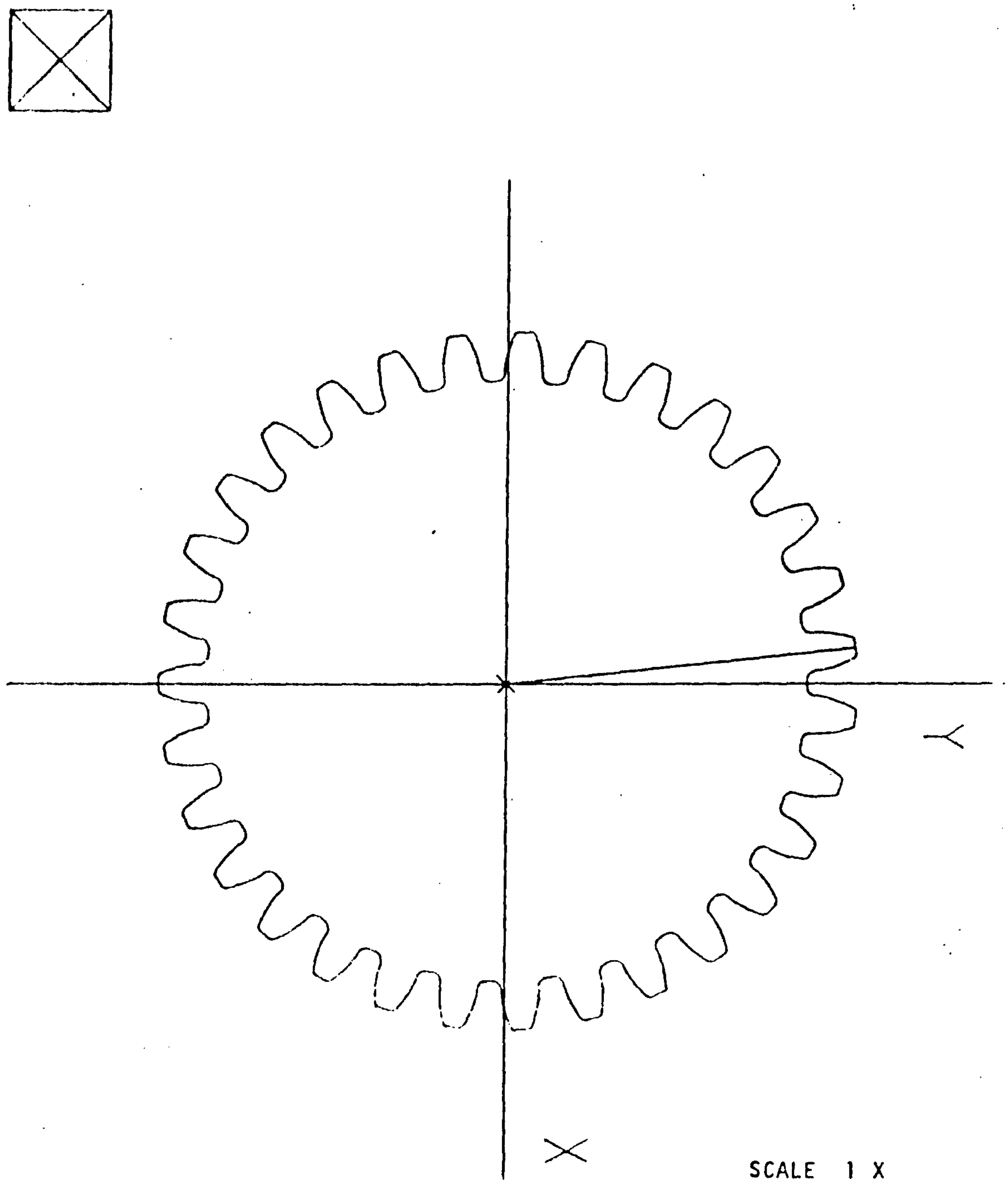


Figure 5-30. Profile of Die Cavity Drawn by CADAM for M-2 Gear Forging Die.

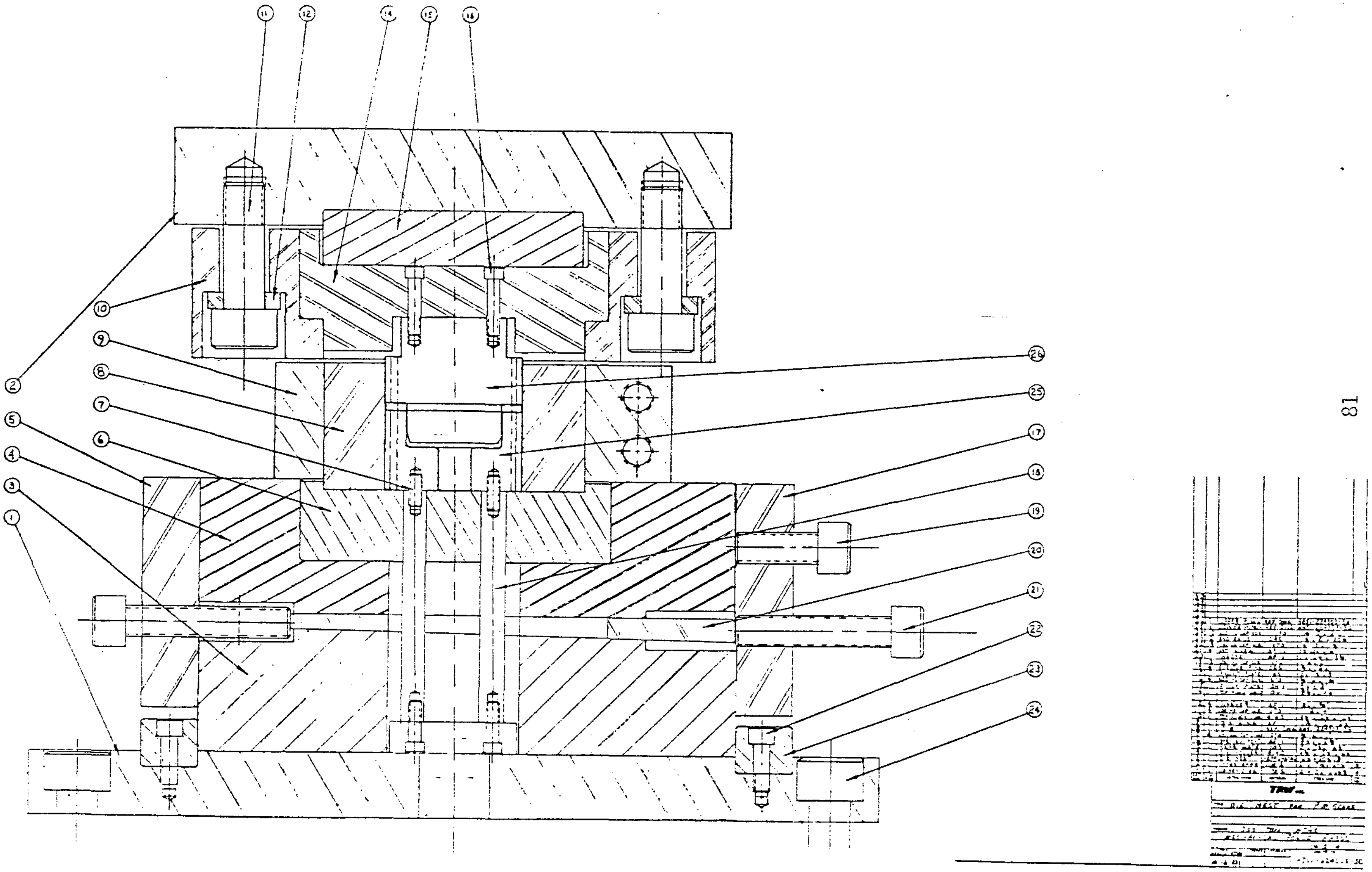


Figure 5-31. Drawing of Tooling Assembly for Forging M-2 Pinion Gear With Forging Tooling in Place.

TABLE 5-11. Die Cavity Data Used by CADAM to Generate NC Tapes for Wire EDM

Major Diameter	4.1941 in.
Minor (Root) Diameter	3.6012 in.
Pitch Diameter	3.9491 in.
Circular Tooth Thickness	0.2001 in.
Base Diameter	3.7109 in.
Root Curvature	0.050 in.
Pressure Angle	20°
Number of Teeth	31
Diametral Pitch	8

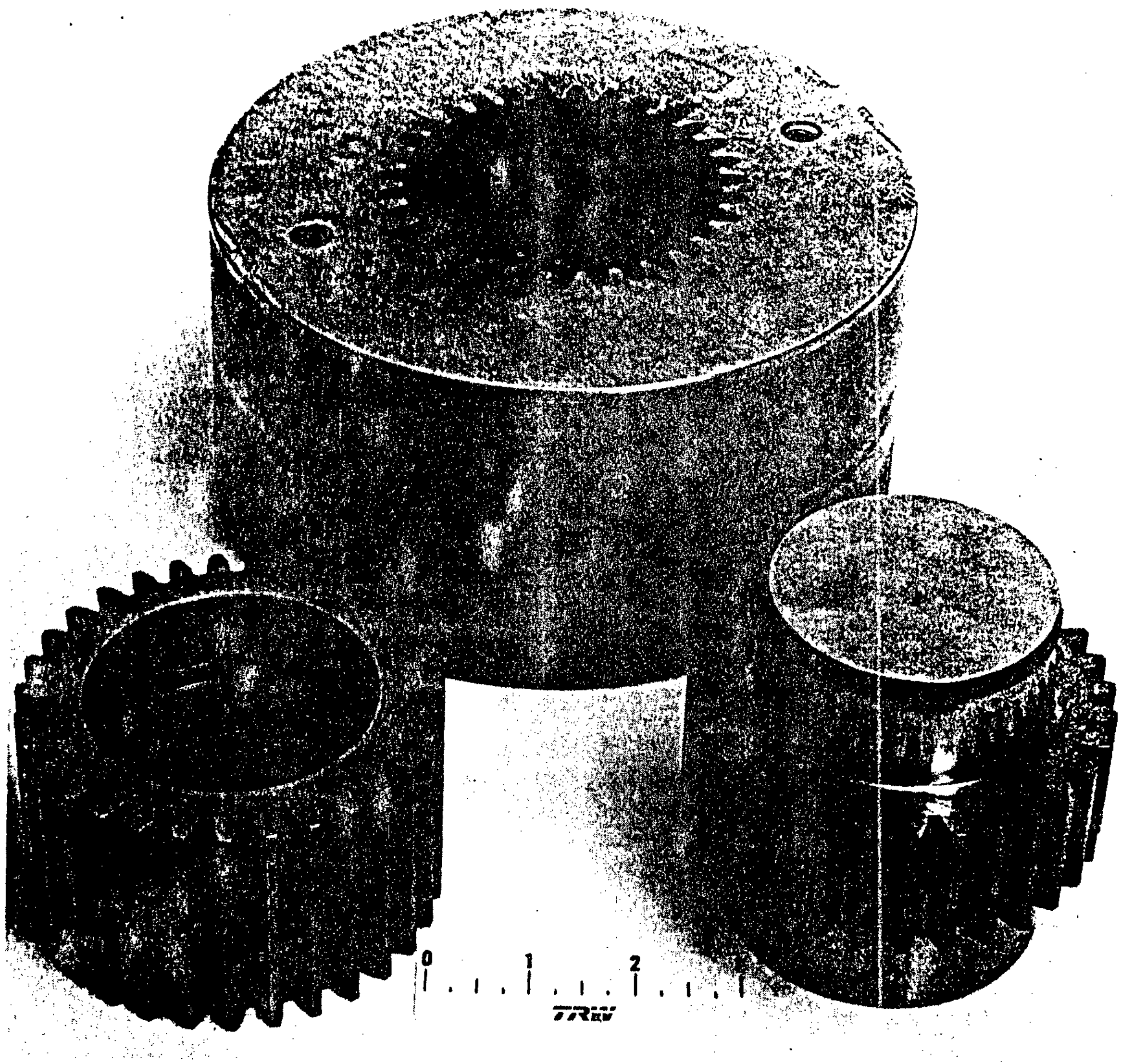


Figure 5-32. Forging Tooling Components for M-2 Pinion Gears.

A set of 26 gears was forged using preheat temperatures of 2100, 2200, and 2300°F. The 10 representative gears are shown in Figure 5-33. M2 gear gorging data are given in Table 5-12. Modified hardening procedures established for the AGT 1500 gears were applied to the M2 gears and are given below.

B. Hardening Procedure for M2 Gears

B.1 Gear Nos. 2, 3, 5, 11, 23, 26, 31

B.1.a: Normalize by heating to 1650°F, holding at heat for one hour and cooling in air to room temperature.

B.1.b: Harden by heating to 1550°F, holding at heat for one hour, and quenching in oil.

B.1.c: Double temper by heating to 475°F, holding at heat for two hours, cooling in air to room temperature, reheating to 475°F, holding at heat for two hours and cooling in air.

B.1.d: Pack carburize at 1700°F for 12 hours, using charcoal provided and cool to room temperature.

B.2 Gear Nos. 4, 6, 7, 12, 24, 27, 32.

B.2.a: Same as A.1.a.

B.2.b: Harden by heating to 1550°F, holding at heat for one hour, and quenching in water.

B.2.c: Same as A.1.c.

B.2.d: Same as A.1.d.

B.3 Gear Nos. 9, 13, 18, 21, 25, 28, 33.

B.3.a: Same as A.1.b.

B.3.b: Same as A.1.c.

B.4. Gear Nos. 10, 14, 22, 29, 30.

B.4.a: Same as A.2.b.

B.4.b: Same as A.1.c.

Of the 26 gears, three gears were chosen and were carburized and ground to meet the hardness and dimensional specification is required for 8620H steels. Gear grinding was carried out by Midwest Gear Corporation, Twinsburg, Ohio. The 20 best heat-treated gears, including the three which were carburized and ground, were delivered to TACOM for inspection and testing.

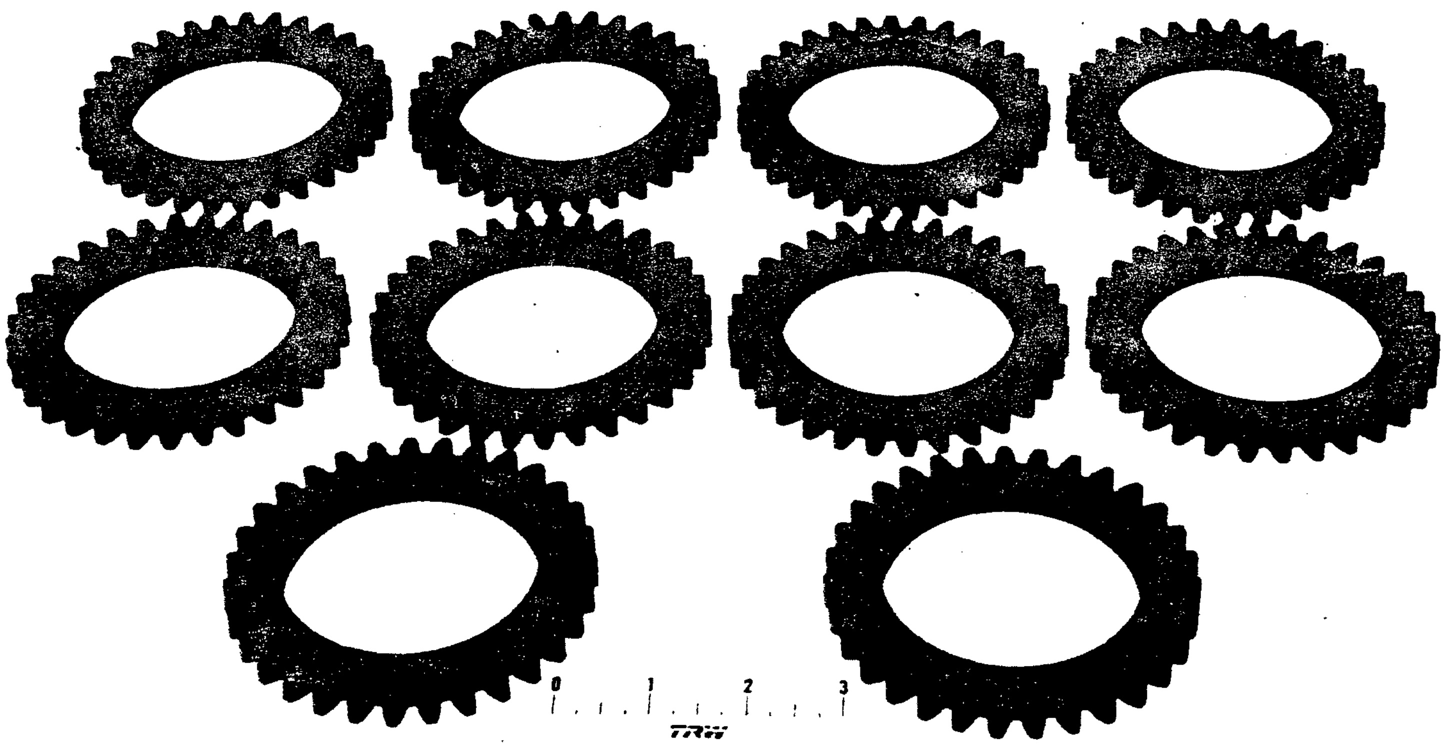


Figure 5-33. As-Forged M-2 Pinion Gears.

TABLE 5-12. M-2 Gear Forging Data

Gear Number	Alloy Composition	Preform Height(in.)	Preform Weight(gm)	Forged Weight(gm)	Preheating Temp. (^{o}F)	Minor Diameter(inch)	Major Diameter(inch)	Part Height Inch
2	4640	0.85	295	294	2200	3.560/3.564	4.151/4.155	.418/.426
3	4660	0.85	286	285	2200	3.560/3.560	4.149/4.151	.410/.413
4	4660	0.85	283	282	2200	3.555/3.557	4.146/4.149	.403/.407
5	4660	1.0	273	272	2200	3.555/3.557	4.148/4.148	.387/.397
6	4660	1.0	267	266	2200	3.555/3.557	4.142/4.143	.383/.388
7	4640	0.85	297	295	2100	3.556/3.556	4.144/4.144	.425/.430
9	4640	0.85	297	296	2300	3.549/3.553	4.139/4.143	.423/.432
10	4640	0.85	296	295	2300	3.554/3.556	4.142/4.143	.422/.425
11	4640	0.85	301	298	2300	3.549/3.554	4.139/4.144	.423/.434
12	4640	0.85	315	313	2300	3.552/3.554	4.144/4.144	.448/.450
13	4660	0.85	289	287	2300	3.554/3.561	4.140/4.148	.412/.413
14	4660	0.85	294	289	2300	3.563/3.566	4.142/4.150	.402/.449
18	4660	1.0	294	290	2300	3.553/3.556	4.134/4.141	.385/.428
21	4640	0.85	301	298	2200	3.554/3.554	4.143/4.147	.425/.433
22	4640	0.85	303	298	2200	3.553/3.557	4.148/4.150	.425/.431
23	4640	0.85	296	293	2200	3.550/3.557	4.143/4.147	.419/.426
24	4640	0.85	294	292	2200	3.548/3.552	4.145/4.147	.414/.423
25	4640	0.85	289	287	2200	3.550/3.559	4.139/4.148	.393/.438
26	4660	0.85	289	284	2200	3.554/3.560	4.142/4.146	.407/.413
27	4660	0.85	307	303	2200	3.546/3.556	4.137/4.147	.411/.414
28	4660	0.85	288	286	2200	3.552/3.555	4.138/4.145	.412/.414
29	4660	0.85	288	286	2200	3.557/3.562	4.146/4.147	.429/.439
30	4660	1.0	293	290	2200	3.559/3.560	4.145/4.145	.418/.419
31	4660	1.0	292	289	2200	3.553/3.559	4.142/4.147	.416/.418
32	4660	1.0	293	289	2200	3.551/3.559	4.138/4.146	.416/.419
33	4660	1.0	293	289	2200	3.555/3.560	4.139/4.144	.412/.429

5.3.4 Discussion of Forging Results. The forging trials carried out for these three different gear geometries served to illustrate and emphasize many critical points about P/M forging. As a recision forging process, control of the process was found to be extremely important from the standpoints of dimensional accuracy and part quality. Every step of the process should be closely monitored.

Preform shape, density, density distribution, and weight must be controlled during compaction and sintering. Light preforms produce undersize parts, heavy performs produce oversize parts and can damage the tools, and preforms with improper mass distribution result in defective and out-of-tolerance parts.

Sintering could be combined with preheating for energy conservation. Time at temperature was found to be important for avoiding workability problems. For a preheat temperature of 2200°F (1204°C), 30 minutes was for heating green preforms.

The preform temperature and die temperature affect the final part size and can be used to adjust as-forged dimensions. Higher preform temperatures and lower die temperatures produce smaller parts than the opposite conditions. A preform temperature of 2200°F (1204°C) and die temperatures of 350° to 550°F (175° to 290°C) were shown to be optimal for these parts.

Forging the cycle time is important and should be consistent. A time of four seconds proved to be repeatable for manual transfer from the furnace to the die cavity, and it was fast enough to avoid oxidation of the preform.

Commercially available 4600 steel powder, produced by water atomization and blended with graphite, was found to be acceptable for these high-performance applications. Gears of 4620, 4640 and 4660 composition were forged from sintered preforms. NASA testing showed that carburized gears with forged-plus-ground teeth were capable of operating under conditions of high Hertzian loading without tooth breakage.

Die design and manufacturing using CAD/CAM techniques was necessary for this precisioin forging operation. Wire EDM proved to be an effective method of cutting both the die cavity and punch profile. When possible, the core rod for forging bores should be incorporated into the tope punch. This eases ejection of the forged part from the die cavity.

Lastly, the P/M forging process was demonstrated to be flexible and capable of producing precision parts of high quality. The three gear shapes produced in this program represent different levels of complexity and P/M was capable of producing all three gears. The use of this process for the production of military hardware should be implemented where cost reduction can be forecast.

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Appendix A

IMPLEMENTATION OF COMPUTER-AIDED DESIGN OF PREFORMS

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The original approach to this project included application of the CAD program for preform design developed at the University of Pittsburgh to gear forging. The program was translated to TRW's IBM computer system from the University's DEC 10 system. This software consists of three major sections. First, a geometric description module allows shapes to be described in a manner that is suitable for subsequent calculations. Second, a part is sectioned into regions of different types of metal flow. Then a preform design is determined. This program is interactive, with the user suggesting designs and modifications, and the computer deciding whether or not the design is feasible based on a set of rules contained in a database for that particular combination of material and working conditions.

The geometric description module was modified to allow axisymmetric shapes to be described. From the part description, volume and cross sectional area calculations could be made. For example, the cross sectional area is determined by approximating the contour as a closed polygon. A part drawing can be reduced to dimensional data for this description by use of a digitizer. Then, the area is given by:

$$A = \underline{1} * N_2Y_1 - N_1Y_2 + N_3Y_2 - N_2Y_3 + \ldots + N_nY_{n-1} - N_{n-1}Y_n + N_1Y_n - N_nY_1 \qquad \text{eq. (A1)}$$

where N_a, $N_2, \ldots$, N_n and Y_1, $Y_2, \ldots$, Y_n are coordinates of consecutive corners of the polygon with respsect to a cartesian coordinate system. Volume can be found by rotating this area about an axis of symmetry. The program is written in Fortran IV, and is useful for determining areas and volumes of complex axisymmetric shapes. This category includes preform shapes for most gears. However, it is not developed to the point of calculating volumes for parts with internal or external projections, such as gears or splines.

It became apparent at this point that CAD preforms for gear forging was beyond the scope of this program. A database of gear shapes with metal flow descriptions would have to be generated to make this software useful. This in itself was a great task. Therefore, the application of CAD to this program shifted from complete preform design to the application of existing CAD packages where possible to aid in design calculations. CADAM was found to be very useful in this type of approach. CADAM could not be used to design a preform by itself. After all, CADAM is nothing more than a computerized drafting package with some engineering calculation potential. Nevertheless, the calculation power of CADAM was extremely useful for die dimensioning and area and volume calculations. Such packages could be used interactively to effectively determine a preform design. User input was the sole design criterion, but CADAM made fast work of laborious volume and mass distribution calculations.

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Appendix B

DIE DIMENSIONING CALCULATIONS

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Die dimensions are calculated on the bases of thermal and mechanical considerations. For many parts, it is adequate to merely consider only thermal expansion factors because any mechanical factors are sufficiently small that final dimensions are not affected. For these gears, both approaches to tooling dimensioning were used. the NASA test gear tooling was dimensioned strictly on thermal considerations, while the tooling for the larger diameter AGT 1500 accessory gears and the M2 gear were designed using both thermal and mechanical considerations. These approaches are detailed below.

B.1 Thermal Considerations for Tooling Dimensioning

The equation used to calculate room temperature die cavity dimensions for forging a part of a given size is:

$$D_D \times (1+ \alpha_D \times \Delta T_D) = D_P \times (1+ \alpha_P \times \Delta T_P) \qquad \text{eq. (B1)}$$

where D and P refer to die and part values for diameter, thermal expansion coefficient and temperature difference from ambient to operating temperature. This equation is based on the die cavity diameter being equal to the part diameter at the forging conditions. Therefore, the temperature of the die and the temperature of the part just prior to ejection must be determined. These values can be substituted in the equation, along with the room temperature part diameter, to calculate the room temperature diameter of the die. Conversely, if the die diameter is known, the size of the part that may be forged in the die can be calculated.

B.2 Thermal and Mechanical Considerations for Tooling Dimensioning

A more accurate determination of room temperature tooling dimensions takes into account mechanical compliances between the part being forged and the tooling. Consider the case for forging a solid cylinder. Figure B-1 shows the dimensional changes that both the die and the part see during the process. Mathematically, these are represented by:

$$D_D + \Delta d_1 + \Delta d_2 - \Delta d_3 = D_P + \Delta a_1 - \Delta a_2 \qquad \text{eq. (B2)}$$

where the terms are defined in Figure B-1. The terms with subscript 1 are thermal terms as determined in the previous section. The terms with subscript 2 and 3 are mechanical terms.

$$\Delta a_1 = D_P \times \alpha_P \times \Delta T_P \qquad \text{eq. (B3)}$$

The part diameter at the ejection temperature would therefore be:

$$D_P = D_P + \Delta a_1$$

Δa_2 - The elastic expansion of the part upon ejection from the die is calculated by:

$$\Delta a_2 = D_p \times (P/E_p) \times (1- {}_p) \qquad \text{eq. (B4)}$$

where P is the pressure applied to the part by the die prior to ejection, E_p is the elastic modulus of the part at the ejection temperature and ${}_p$ is the Poisson ratio of the part. A first approximation of P is the yield strength of the part at the ejection temperature.

Δd_1 - The thermal expension of the die cavity from room temperature to the die preheat temperature is given by:

$$\Delta d_1 = D_D \times {}_D \times \Delta T_D \qquad \text{eq. (B5)}$$

Therefore, the inner diameter of the die at the preheat temperature equals:

$$D_D = D_D \times (1 + {}_D \times \Delta T_D$$

Δd_2 - The die cavity expansion due to forging load is calculated by:

$$\Delta d_2 \quad D_D \cdot \frac{P}{E_D} \cdot \quad \frac{D^2_{OD} + D_p^{\,2}}{D^2_{OD} - D^2_P} \quad + \quad {}_D \qquad \text{eq. (B6)}$$

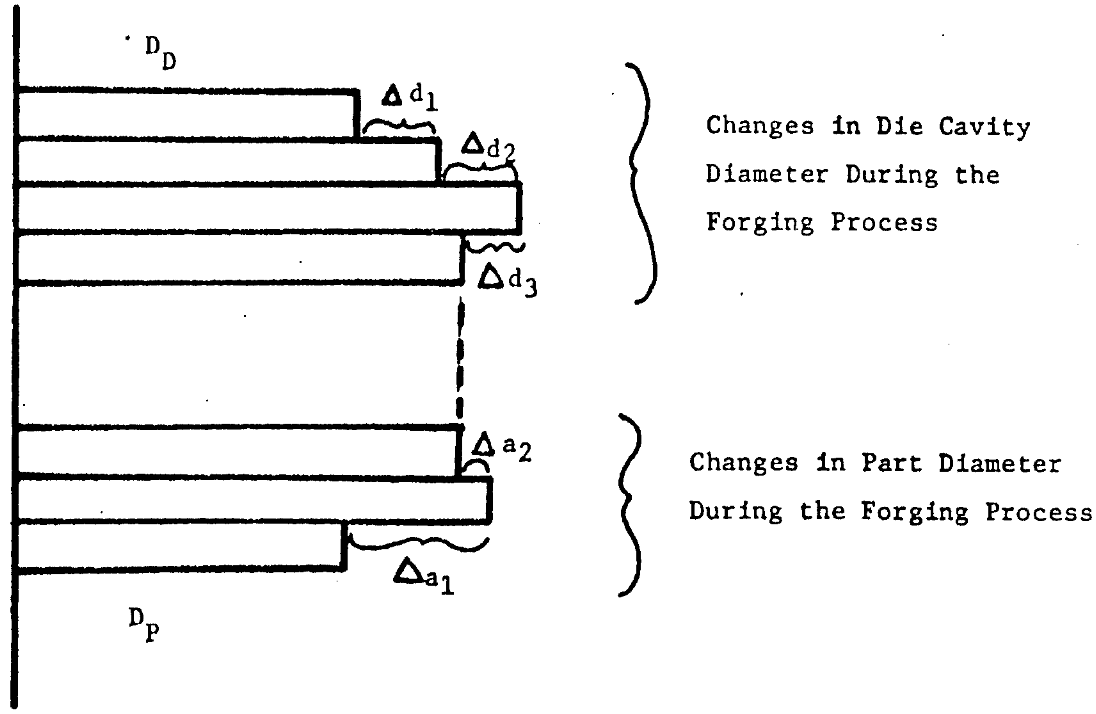
where P is the forging pressure, E_D is the elastic modulus of the die material, D_{OD} is the outer diamter of the ring die, D_p is the part diameter, and ${}_D$ is the Poisson ratio of the die material.

Δd_3 - The elastic contraction of the ring die as the forging load is released is calculated by:

$$\Delta d_3 = (D_D + \Delta d_2) \cdot \frac{Y_P}{D_D} \cdot \frac{D_{OD}^2 + (D_D + \Delta d_2)2}{D_{OD}^2 - (D_D + \Delta d_2)^2} + {}_D$$

where Y_P is the yield strength of the part the other terms are as defined previously.

These equations rely on accurate data for the forging process and for the necessary mechanical and physical properties of the materials involved. Be aware that the property values are for forging temperatures, not room temperature. The influence of these various variables on final dimensions is shown in figures B-2 through B-8. From these figures, it is clear that thermal expansion terms of the workpiece and die material have the greatest affect on final dimensions. Thus, the values of the expansion coefficients are critical to the accuracy of the predicted dimensions as are the temperatures involved. Of the mechanical properties, the elastic modulus of the die has a high slope as shown in Figure B-8, which is indicative of a strong effect on final dimensions. Of equal importance are the variables which are not discussed. Transfer time from the furnace to the die has a major effect on ejection temperature, as well as part quality through control of internal oxidation. Time in the die cavity is also important for the same reasons. This model is still a simple approximation of a complex process. The future will see improvements in such models by adapting accurate heat transfer analysis and stress analysis using finite modeling to this problem.



D_D = room temperature diameter of die cavity

Δd_1= increase in die cavity diameter due to thermal expansion

Δd_2= elastic expansion of die cavity under forging pressure

Δd_3=elastic contraction of die cavity upon release of forging pressure

D_P = desired diameter of part

Δa_1= thermal contraction from ejection temperature to room temperature

Δa_2= elastic expansion of part upon ejection from die

Figure B-1. Dimensional Changes of the Die and the Part that Occur During the P/M Forging Process.

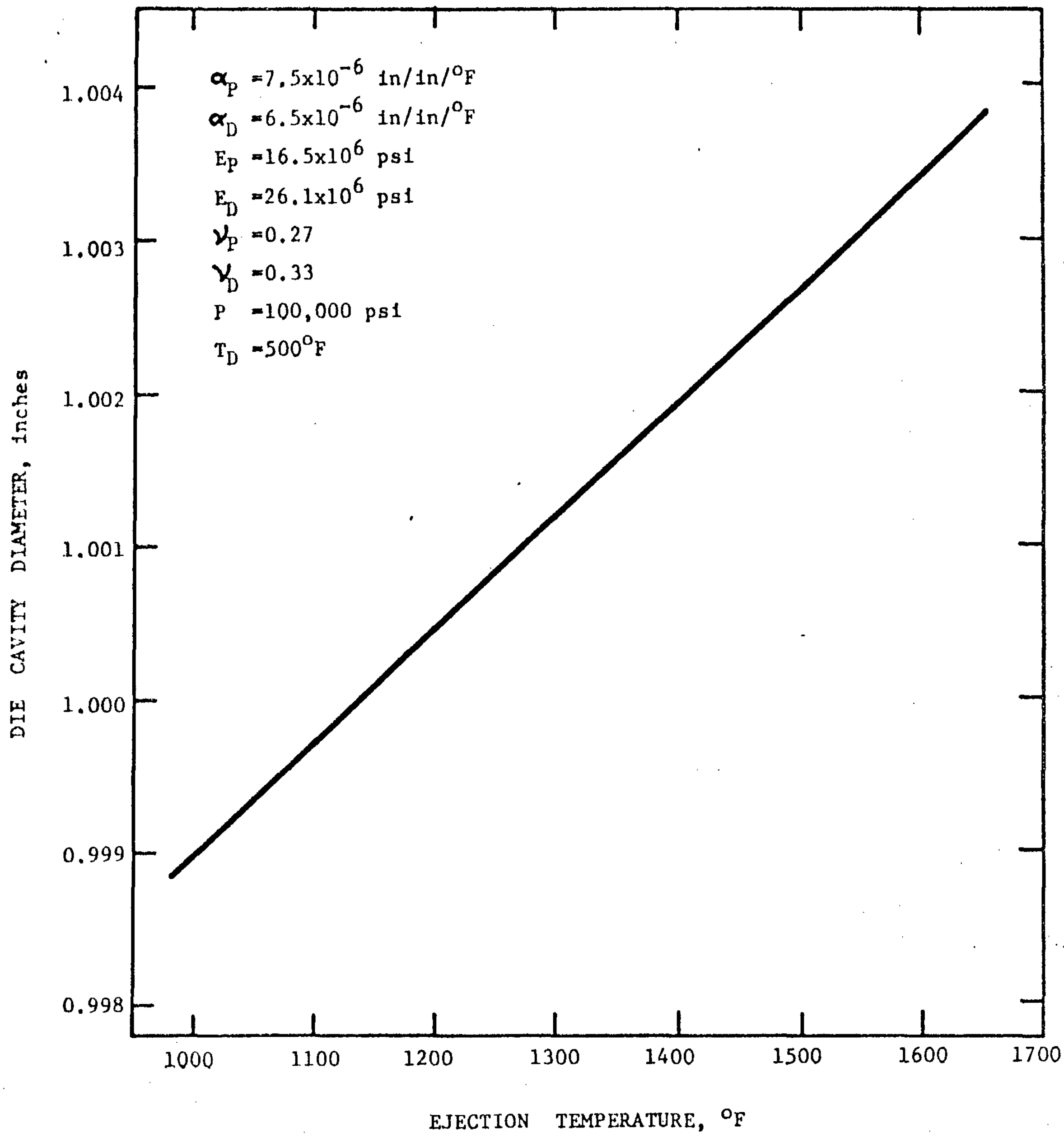


Figure B-2. Effect of Part Ejection Temperature on the Die Cavity Diameter Needed to Forge a Solid Cylinder of 1.000 inch in Diameter.

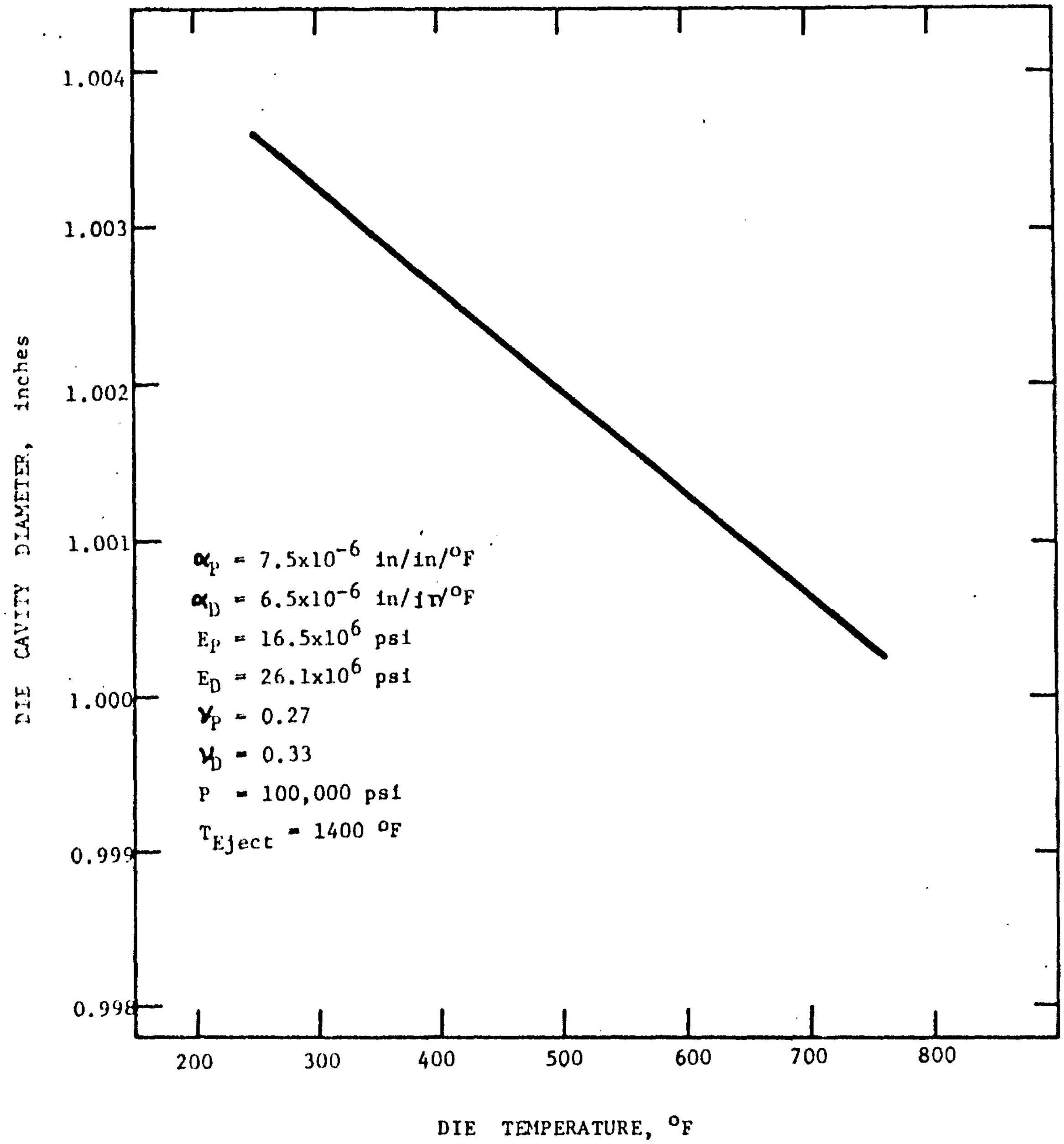


Figure B-3. Effect of Die Temperature on the Die Cavity Diameter Needed to Forge a Solid Cylinder of 1.000 inch in Diameter.

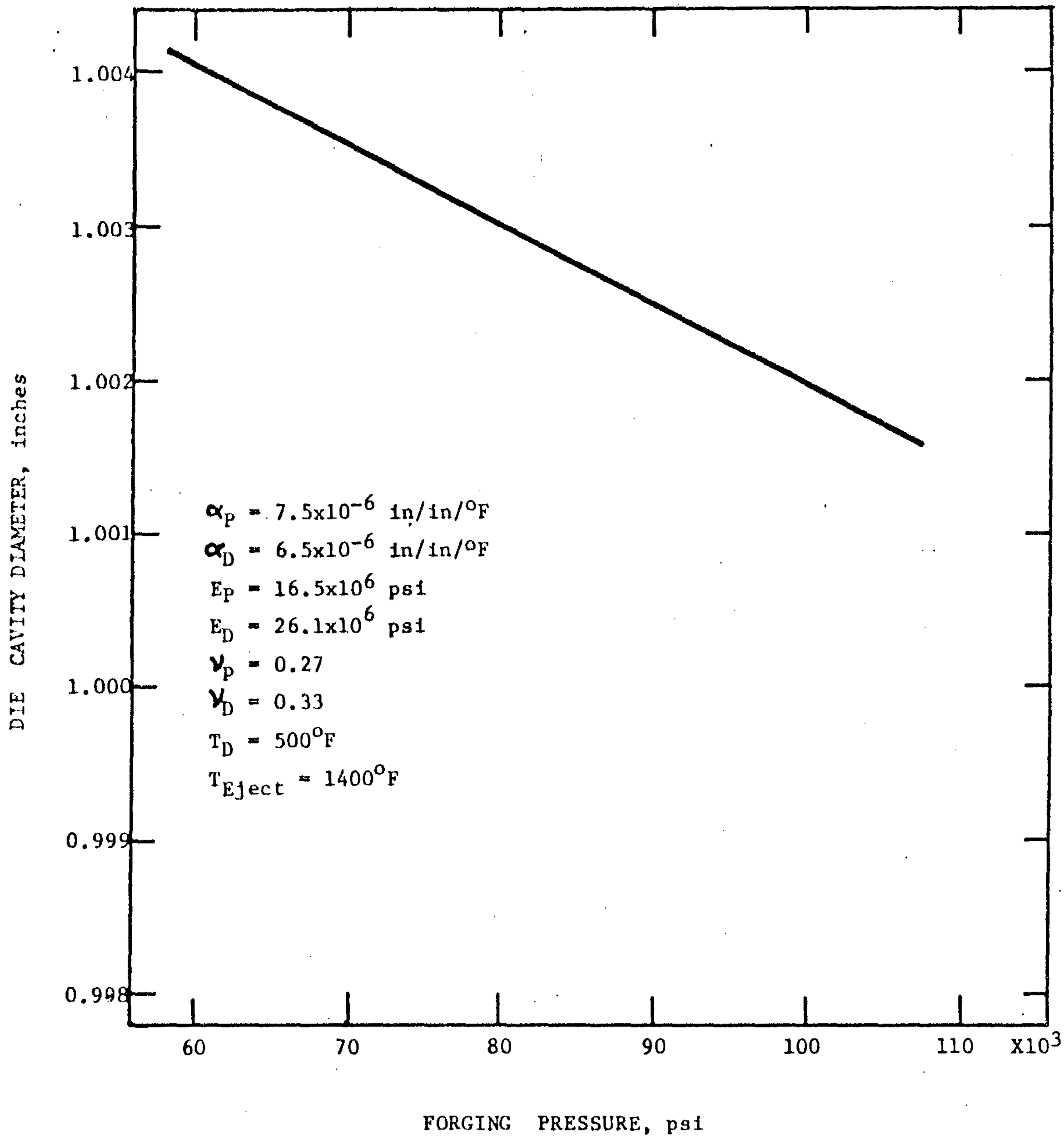


Figure B-4. Effect of Forging Pressure on the Die Cavity Diameter Needed to Forge a Solid Cylinder of 1.000 inch in Diameter.

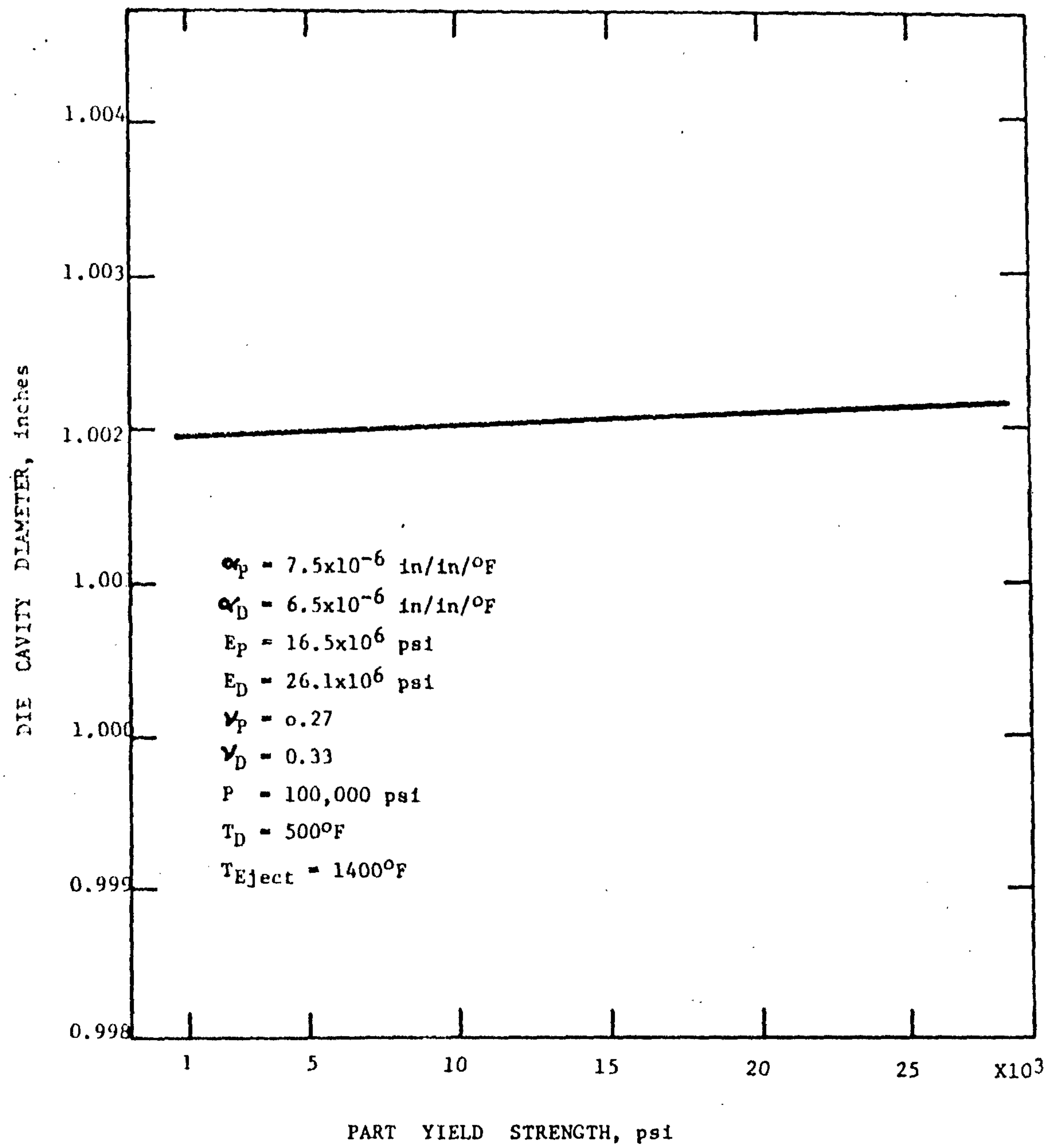


Figure B-5. Effect of the Part Yield Strength on the Die Cavity Diameter Needed to Forge a Solid Cylinder of 1.000 inch in Diameter.

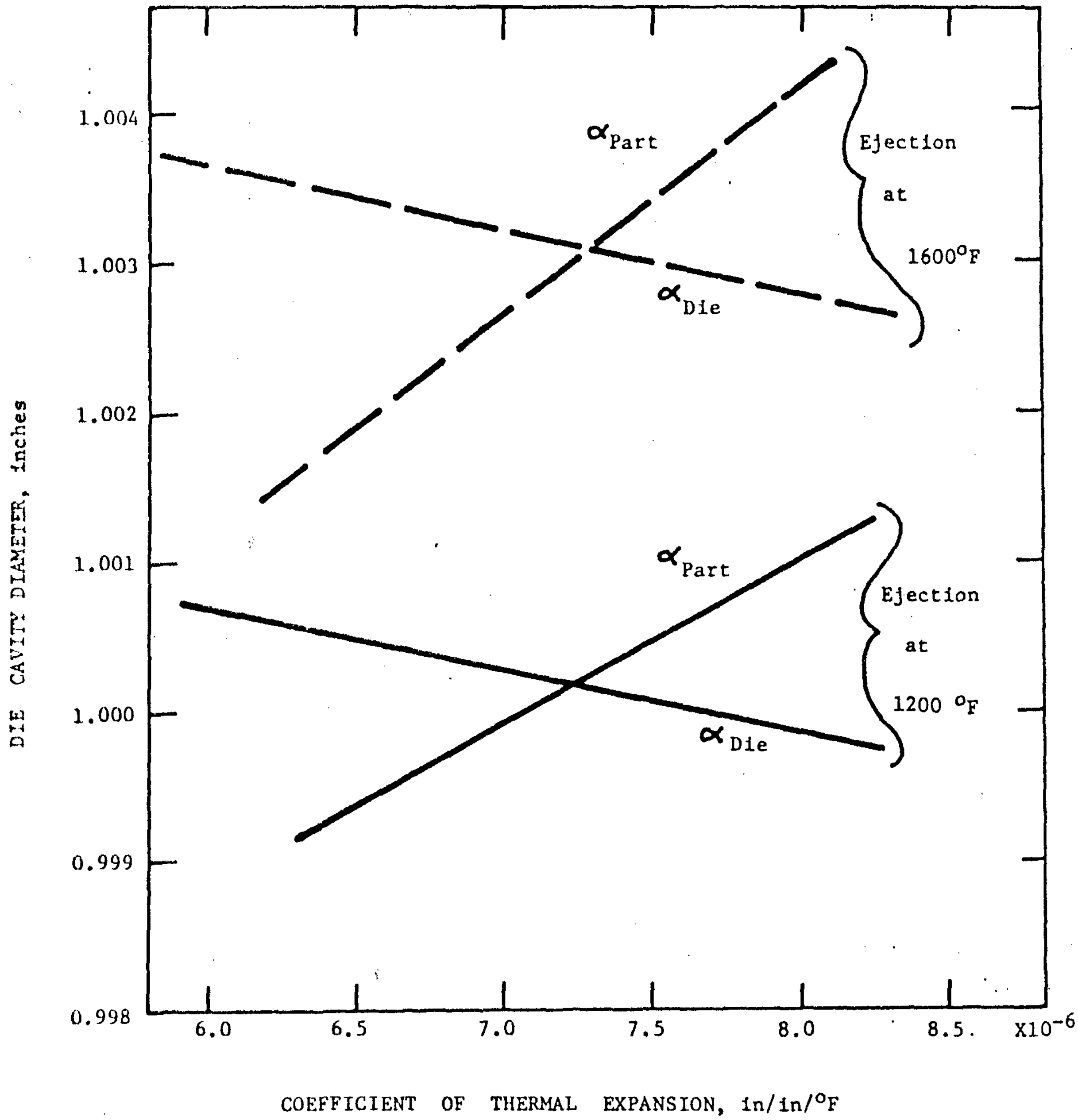


Figure B-6. Effect of Thermal Expansion Coefficients of the Part and Die on the Die Cavity Diameter Needed to Forge a Solid Cylinder of 1.000 inch in Diameter. Modulus, Poisson Ratio, Forging Pressure and Die Temperature are the Same as Figure B-5.

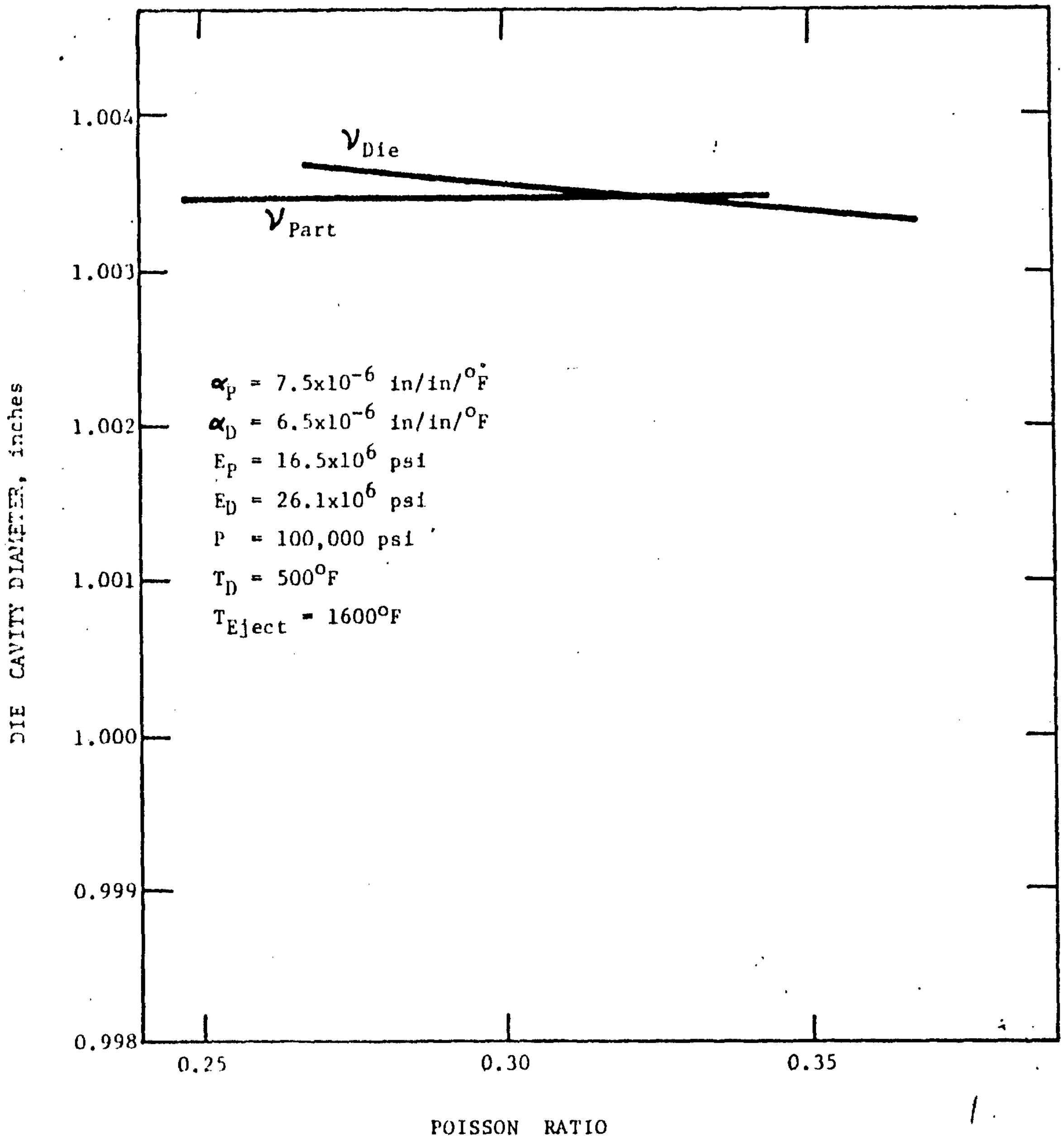


Figure B-7 Effect of Poisson Ratio of the Die and the Part on the Die Cavity Diameter Needed to Forge a Solid Cylinder of 1.000 inch in Diameter.

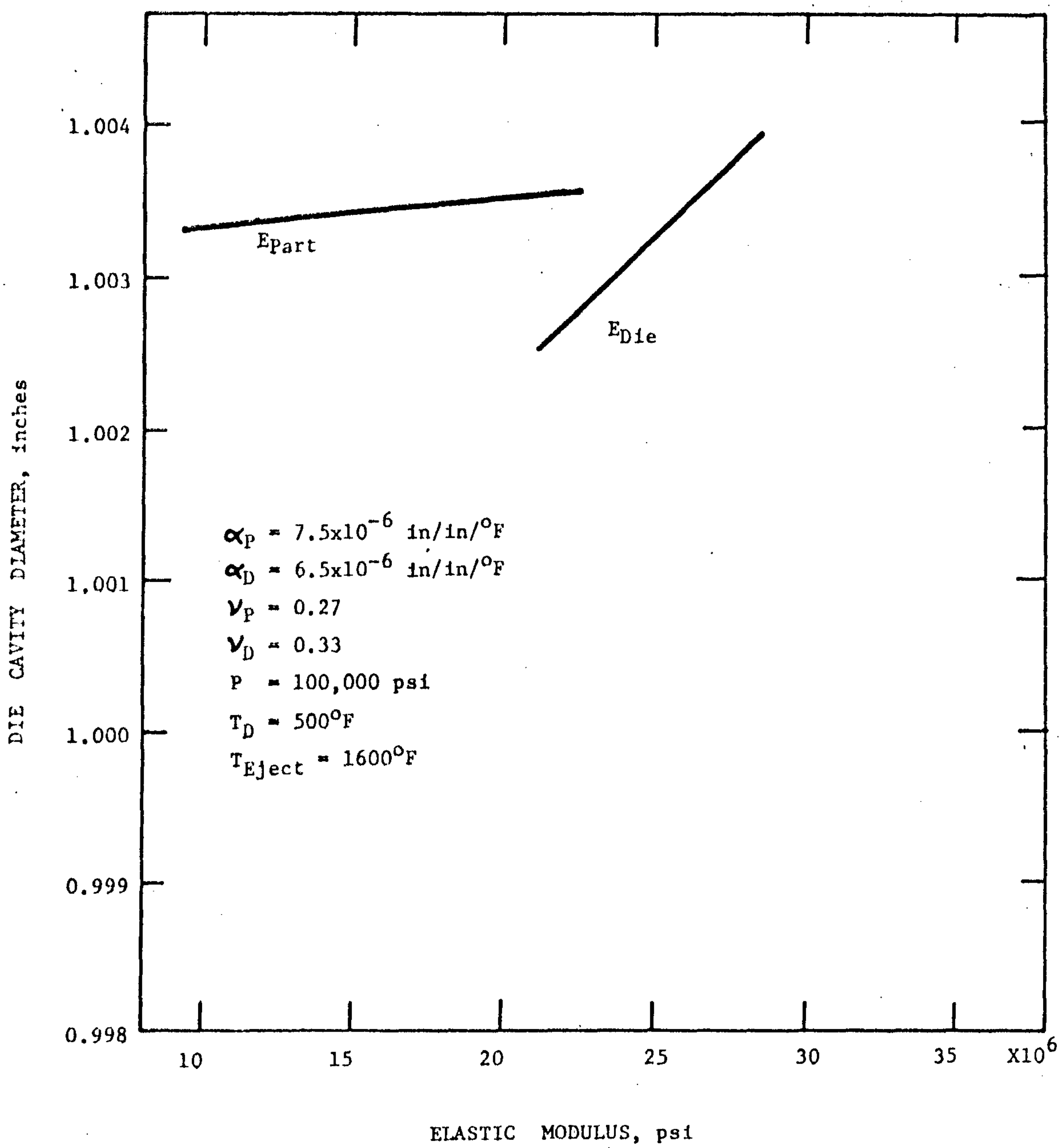


Figure B-8. Effect of Elastic Modulus of the Die and the Part on the Die Cavity Diameter Needed to Forge a Solid Cylinder of 1.000 inch in Diameter.

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Appendix C

COST ANALYSIS

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The production quotas for the AGT 1500 No. 6 gear and the M2 power take-off gear are 1,000 gears of each type per year. For P/M forging, all 1,000 gears should be produced in one run. Typical production runs for P/M forgings are 25,000 parts or more for economical advantage of the process. For parts such as these, which place a premium on quality and reliability, lower volumes can be produced economically. Because of the ability to automate the process, the time and cost of tooling setup, the production runs should be as large as possible. Using a computer program developed by Deformation Control Technology, cost projections are presented below for high quality powder forged gears. Grinding is included as a finishing step. For comparison, the cost to TACOM for the M2 gear in lots of 1,000 is $35 per gear by conventinal manufacturing.

For a completely automated P/M forging line, a cost of less than $9.50 is projected in Table C-1. This figure assumes that the equipment purchased for P/M forging is depreciated at a daily rate for the time that is it used for forging of this gear. All other necessary equipment, such as grinding equipment, is in-house and is not included in this equipment cost. No building or office costs are included in this figure.

From the production standpoint, labor and overhead are charged for each operation. Inspection has been included in the overhead rate for the production steps. For this automated line, a production rate of six pieces per minute was used. This value is slightly conservative for an automated line, but it allows for production disturbances and minor delays.

The summary portion of the output shows that finishing costs dominate the unit part cost, followed by tooling costs, overhead costs, and material costs. Finishing includes heat treat and grinding, with grinding being the major cost. An automated grinding setup is assumed for accurate and fast fixturing for grinding, or else grinding costs would be prohibitive. Tooling is high in this case because two sets of tooling are required, and a life of 3,000 forgings was assigned to the forging tooling. Due to the low production quantity, it was projected that the tooling would degrade while on the shelf, and that it would need to be replaced every three years for reasons other than die wear. Overhead is high because it includes inspection and management costs.

A sensitivity analysis is included which shows the effect of varying assumed costs by 50 per cent to 100 per cent greater than baseline value. The unit cost is not significantly changed for any single value variation, and it remains well below the $35 figure for conventionial production (which includes profit while the projected unit cost does not). If all values varied at the same time, the projected unit cost would be $14,748, which is still below the current price, even with a 50 per cent profit added. Clearly, for an automated P/M forging line, the M2 gear can be produced by P/M forging at a cost reduction from current methods.

For a manual setup, such as the R&D facility at TRW-MMTC, P/M forging is not economical, as shown in Table C-2. This setup entails manual furnace loading, unloading, and forging. Production rates would drop significantly, down to one foring every 20 minutes. Finishing costs for nonproduction equipment would also rise dramatically. A projected cost for a laboratory-type facility is $139,125 per gear. Sensitivity analysis shows that this cost could be significantly higher. Comparison of Tables C-1 and C-2 shows that production must involve automated handling for P/M forging to be economical.

TABLE C-1. Production Costs for Powder Forging of M-2 Power Take-Off Gear. (I): Automated Production

Summary of Input Data

Annual Interest Rate = 15%
Weeks worked per year: 48 Days worked per week: 5
Yearly production of 1,000 parts
will be produced in runs of 1,000 parts
with a rejection rate of 5%.

Production Times and Labor Costs

OPERATION	Rate.pcs./min.	No. Men	Labor Charge/Year
Compaction	6	1	$26.250
Sintering	6	1	$26.250
Forging	6	2	$55.417
Inspection	1	0	$ 0.000
Set-Up Compaction		1	$76.000
Set-Up Forging		1	$76.000

Total Labor Cost per Yearly Production = $259.917

Overhead Burden for Production Operations

OPERATION	BURDEN %	
Compaction	450	$118.125
Sintering	400	$105.000
Forging	450	$249.375
Inspection	0	$ 0.000
Set-Up Compaction	450	$342.000
Set-Up Forging	450	$342.000

Total Overhead Cost per Year = $1,156.500

TABLE C-1. Production Costs for Powder Forging of M-2 Power Take-Off Gear. (I): Automated Production. (Continued)

Cost of Non-Machinery Items

Building Cost is 0 and life is 1 year.
Office Cost is 0 and life is 1 year.

Total Facilities Cost per Lot = $0.000

Cost of Machinery

MACHINE	COST	LIFE (yrs.)
Compaction Press	$350,000	15
Sintering Furnace	$125,000	12
Forging Press	$650,000	15

Total Machinery Cost per year = $125.381

Tooling Requirements and Cost

Tool Item	Cost	Life (pcs.)
Compaction Die Set	$7,500	100,000
Forging Die Set	$7,500	3,000

Total Tooling Cost per Lot = $2,703.750

Raw Material Requirements and Cost

Raw Material	Wt. per Part	Cost per Lb.	Cost per Part
Preblended 4600 Powder	.66	.49	.3234

Total Raw Materials Cost per Lot = $339.570

Finishing Costs per 100 Parts

OPERATION	LABOR COST	BURDEN
Normalizing	2	6
Carburize/Temper	3	10.2
Ream Bore	20	50
Grind Teeth	100	300

TABLE C-1. (Continued)
SUMMARY OF PRODUCTION COSTS PER PART

Total Number of Parts	=	1,000 in lots of 1,000 parts.
Non-Machinery Cost per Part	=	0.000
Machinery Cost per Part	=	0.125
Raw Materials Cost per Part	=	0.340
Tooling Cost per part	=	2.704
Inspection Cost per part	=	0.000
Labor Cost per part	=	0.108
Set-Up Costs per part	=	0.152
Overhead Costs per part	=	1.157
Finishing Costs per part	=	4.912
Cost of Purchased Parts	=	0.000
Production Cost per Part	=$	9.497

The table below is a compilation of production costs on a per part basis that shows the effect of the listed variable values on part cost. Each of the eight listed variables has had its value varied from 50% lower to 100% higher than its baseline value. The change in unit cost is shown in each column for the particular variable. For each column, only that variable is changed; all other variables are held at baseline values. Thus, the individual effect of that variable can be seen.

TABLE OF SENSITIVITY OF PRODUCTION COST TO VARIABLE CHANGES

% Dev. From Base	Variable Item							
	No./ Year	Reject Rate	Run Size	Equip. Cost	Tool Cost	Raw Mat. Cost	Labor Rate	Overhead Rate
-50	9.497	9.425	9.915	9.434	8.145	9.327	9.367	8.919
-40	9.358	9.446	9.497	9.447	8.416	9.361	9.393	9.035
-30	9.258	9.467	9.497	9.460	8.686	9.395	9.419	9.150
-20	9.184	9.489	9.497	9.472	8.956	9.429	9.445	9.266
-10	9.126	9.510	9.497	9.485	9.227	9.463	9.471	9.381
0	9.497	9.531	9.497	9.497	9.497	9.497	9.497	9.497
10	9.421	9.553	9.079	9.510	9.767	9.531	9.523	9.613
20	9.358	9.574	9.079	9.522	10.038	9.565	9.549	9.728
30	9.304	9.595	9.079	9.535	10.308	9.599	9.575	9.844
40	9.258	9.616	9.079	9.547	10.579	9.633	9.601	9.960
50	9.218	9.638	9.079	9.560	10.849	9.667	9.627	10.075
60	9.184	9.659	9.079	9.572	11.119	9.701	9.653	10.191
70	9.153	9.680	9.079	9.585	11.390	9.735	9.679	10.307
80	9.126	9.702	9.079	9.597	11.660	9.769	9.705	10.422
90	9.101	9.723	9.079	9.610	11.930	9.803	9.731	10.538
100	9.268	9.744	9.079	9.622	12.201	9.837	9.757	10.654

TABLE C-1. (Continued)

PRODUCTION TIMES

Compaction	0.365	days
Sintering	0.365	days
Forging	0.365	days

These times are for yearly production of 1000 parts.

TABLE C-2. Production Costs for Powder Forging of M-2 Powder Take-Off Gear. (II): Laboratory Production.

Summary of Input Data

Annual Interest Rate = 15%
Weeks worked per year: 48 Days worked per week: 5
Yearly production of 1,000 parts
will be produced in runs of 1,000 parts
with a rejection rate of 5%.

Production Times and Labor Costs

OPERATION	Rate. pcs./min.	No. Men	Labor Charge/Year
Compaction	.1	1	$1,575.000
Sintering	.1	1	$1,575.000
Forging	.05	2	$6,650.000
Inspection	1	0	$0.000
Set-Up Compaction		1	$76.000
Set-Up Forging		2	$152.000

Total Labor Cost per Yearly Production = $10,028.000

Overhead Burden for Production Operations

OPERATION	BURDEN %	
Compaction	450	$ 7,087.500
Sintering	400	$ 6,300.000
Forging	450	$29,925.000
Inspection	0	$ 0.000
Set-Up Compaction	450	$ 342.000
Set-Up Forging	450	$ 684.000

Total Overhead Cost per year = $44,338.500

TABLE C-2. Production Costs for Powder Forging of M-2 Powder Take-Off Gear. (II): Laboratory Production. (Continued)

Cost of Non-Machinery Items

Building Cost is 0 and life is 1 year.
Office Cost is 0 and life is 1 year.

Total Facilities Cost per Lot = $0.000

Cost of Machinery

MACHINE	COST	LIFE (yrs.)
Compaction Press	$350,000	15
Sintering Furnace	$125,000	12
Forging Press	$650,000	15

Total Machinery Cost per year = $10,030.470

Tooling Requirements and Cost

Tool Item	Cost	Life (pcs.)
Compaction Die Set	$7,500	100,000
Forging Die Set	$7,500	3,000

Total Tooling Cost per Lot = $2,703.750

Raw Material Requirements and Cost

Raw Material	Wt. per Part	Cost per Lb.	Cost per Part
Preblended 4600 Powder	.66	.49	.3234

Total Raw Materials Cost per Lot = $339.570

Finishing Costs per 1 Parts

OPERATION	LABOR COST	BURDEN
Normalizing	.45	2.03
Carburize/Temper	1	4.5
Ream Bore	1.58	7.125
Grind Teeth	10	45

TABLE C-2 (Continued)
SUMMARY OF PRODUCTION COSTS PER PART

Total Number of Parts	=	1,000 in lots of 1,000 parts.
Non-Machinery Cost per Part	=	0.000
Machinery Cost per Part	=	10.030
Raw Materials Cost per Part	=	0.340
Tooling Cost per part	=	2.704
Inspection Cost per part	=	0.000
Labor Cost per part	=	9.800
Set-Up Costs per part	=	0.228
Overhead Costs per part	=	44.339
Finishing Costs per part	=	71.685
Cost of Purchased Parts	=	0.000

Production Cost per Part = $139.125

The table below is a compilation of production costs on a per part basis that shows the effect of the listed variable values on part cost. Each of the eight listed variables has had its value varied from 50% lower to 100% higher than its baseline value. The changes in unit cost is shown in each column for the particular variable. For each column, only that variable is changed; all other variables are held at baseline values. Thus, the individual effect of that variable can be seen.

TABLE OF SENSITIVITY OF PRODUCTION COST TO VARIABLE CHANGES

% Dev. From Base	Variable Item No./ Year	Reject Rate	Run Size	Equip. Cost	Tool Cost	Raw Mat. Cost	Labor Rate	Overhead Rate
-50	139.125	137.575	139.752	134.110	137.773	138.956	134.111	116.956
-40	138.916	137.895	139.125	135.113	138.044	138.989	135.114	121.390
-30	138.767	138.216	139.125	136.116	138.314	139.023	136.117	125.824
-20	138.655	138.536	139.125	137.119	138.585	139.057	137.120	130.258
-10	138.568	138.856	139.125	138.122	138.855	139.091	138.123	134.691
0	139.125	139.177	139.125	139.125	139.125	139.125	139.125	139.125
10	139.011	139.497	138.498	140.128	139.396	139.159	140.128	143.559
20	138.916	139.817	138.498	141.131	139.666	139.193	141.131	147.993
30	138.836	140.138	138.496	142.134	139.936	139.227	142.134	152.427
40	138.767	140.458	138.498	143.137	140.207	139.261	143.136	156.861
50	138.707	140.778	138.498	144.141	140.477	139.295	139.139	161.295
60	138.655	141.098	138.498	145.144	140.748	139.329	145.142	165.728
70	138.609	141.419	138.498	146.147	141.018	139.363	146.145	170.162
80	138.568	141.739	138.498	147.150	141.288	139.397	147.148	174.596
90	138.531	142.059	138.498	148.153	141.559	139.431	148.150	179.030
100	138.812	142.380	138.498	149.156	141.829	139.465	149.153	183.464

TABLE C-2. (Continued)

PRODUCTION TIMES

Compaction	21.875	days
Sintering	21.875	days
Forging	43.750	days

These times are for yearly production of 1,000 parts.

TABLE C-3. Production Costs for Powder Forging of AGT 1500 No. 6 Accessory Gear: (I) Automated Production.

Summary of Input Data

Annual Interest Rate = 15%
Weeks worked per year: 48 Days worked per week: 5
Yearly production of 1,000 parts
will be produced in runs of 1,000 parts
with a rejection rate of 5%.

Production Times and Labor Costs

OPERATION	Rate. pcs./min.	No. Men	Labor Charge/Year
Compaction	6	1	$26.250
Sintering	6	1	$26.250
Forging	6	2	$52.500
Inspection	1	0	$ 0.000
Set-Up Compaction		1	$72.000
Set-Up Forging		1	$72.000

Total Labor Cost per Yearly Production = $249.000

Overhead Burden for Production Operations

OPERATION	BURDEN %	
Compaction	450	$118.125
Sintering	400	$105.000
Forging	450	$236.250
Inspection	0	$ 0.000
Set-Up Compaction	450	$324.000
Set-Up Forging	450	$324.000

Total Overhead Cost per Year = $1,107.375

TABLE C-3. Production Costs for Powder Forging of AGT 1500 No. 6 Accessory Gear: (I) Automated Production. (Continued)

Cost of Non-Machinery Items

Building Cost is 0 and life is 1 year.
Office Cost is 0 and life is 1 year.

Total Facilities Cost per Lot = $0.000

Cost of Machinery

MACHINE	COST	LIFE (yrs.)
Compaction Press	$350,000	15
Sintering Furnace	$125,000	12
Forging Press	$650,000	15

Total Machinery Cost per year = $125,381

Tooling Requirements and Cost

Tool Item	Cost	Life (pcs.)
Compaction Tooling	$7,500	100,000
Forging Tooling	$7,500	3,000

Total Tooling Cost per Lot = $2,703.750

Raw Material Requirements and Cost

Raw Material	Wt. per Part	Cost per Lb.	Cost per Part
Preblended 4640 Steel Powder	3.15	.49	1.5435

Total Raw Materials Cost per Lot = $1,620.675

Finishing Costs per 1 Parts

OPERATION	LABOR COST	BURDEN
Normalize	.1	.35
Harden	.3	1.
Ream Bore	.2	.5
Face Part	1.	4.
Grind Teeth	10.	40.

TABLE C-3 (Continued)
SUMMARY OF PRODUCTION COSTS PER PART

Total Number of Parts	=	1,000 in lots of 1,000 parts.
Non-Machinery Cost per Part	=	0.000
Machinery Cost per Part	=	0.125
Raw Materials Cost per Part	=	1.621
Tooling Cost per Part	=	2.704
Inspection Cost per Part	=	0.000
Labor Cost per Part	=	0.105
Set-Up Costs per Part	=	0.144
Overhead Costs per Part	=	1.107
Finishing Costs per Part	=	57.450
Cost of Purchased Parts	=	0.000
Production Cost per Part	=	$63.256

The table below is a compilation of production costs on a per part basis that shows the effect of the listed variable values on part cost. Each of the eight listed variables has had its values varied from 50% lower to 100% higher than its baseline value. The change in unit cost is shown in each column for the particular variable. For each column, only that variable is changed; all other variables are held at baseline values. Thus, the individual effect of that variable can be seen.

TABLE OF SENSITIVITY OF PRODUCTION COST TO VARIABLE CHANGES

% Dev. From Base	Variable Item: No./Year	Reject Rate	Run Size	Equip. Cost	Tool Cost	Raw Mat. Cost	Labor Rate	Overhead Rate
-50	63.256	63.153	63.652	63.193	61.904	62.446	63.132	62.702
-40	63.124	63.180	63.256	63.206	62.175	62.608	63.157	62.813
-30	63.030	63.207	63.256	63.219	62.445	62.770	63.181	62.924
-20	62.959	63.234	63.256	63.231	62.715	62.932	63.206	63.035
-10	62.904	63.261	63.256	63.244	62.986	63.094	63.231	63.145
0	63.256	63.289	63.256	63.256	63.256	63.256	63.256	63.256
10	63.184	63.316	62.860	63.269	63.527	63.418	63.281	63.367
20	63.124	63.343	62.860	63.281	63.797	63.580	63.306	63.478
30	63.073	63.370	62.860	63.294	64.067	63.742	63.331	63.588
40	63.030	63.397	62.860	63.306	64.338	63.904	63.356	63.699
50	62.992	63.424	62.860	63.319	64.608	64.067	63.381	63.810
60	62.959	63.451	62.860	63.331	64.878	64.229	63.406	63.921
70	62.930	63.478	62.860	63.344	65.149	64.391	63.430	64.031
80	62.904	63.506	62.860	63.356	65.419	64.553	63.455	64.142
90	62.881	63.533	62.860	63.369	65.690	64.715	63.480	64.253
100	63.058	63.560	62.860	63.382	65.960	64.877	63.505	64.364

TABLE C-3. (Continued)

PRODUCTION TIMES

Compaction	0.365 days
Sintering	0.365 days
Forging	0.365 days

These times are for yearly production of 1,000 parts.